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Imploding Plasma Radiation Sources: Basic Concepts

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This document is prepared as a briefing aid and technical primer for persons unfamiliar and uninitiated with the theory of imploding plasma radiation sources. It is hoped that it will prove helpful in introducing the basic physics concepts of these sources and in presenting these concepts to newcomers and potential users.

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IMPLODING PLASMA RADIATION SOURCES: BASIC CONCEPTS

INTRODUCTION

This document is prepared as a briefing aid and technical primer for persons unfamiliar and uninitiated with the theory of imploding plasma radiation sources. It is hoped that it will prove helpful in introducing the basic physics concepts of these sources and in presenting these concepts to newcomers and potential users. The figures are included with the text for continuity, and again in full-size format at the end, for use as view-graph materials. DNA support is gratefully acknowledged for the more extensive research of which this is a by-product. In particular, we would like to thank Mr. Jon Farber and Majors H. Soo and J. Benson for suggesting the idea of writing a primer and their encouragement during its documentation. We also thank members of the Plasma Radiation Branch for their contributions and interest in this primer.

Manuscript approved May 18, 1984.

IMPLODING PLASMA RADIATION SOURCES:

WHAT THEY DO

- IMPLODING PLASMA DISCHARGES

  - CONVERT 100-200 NS PULSES OF EM ENERGY INTO KINETIC ENERGY OF PLASMA RUN-IN.

  - CONVERT KINETIC ENERGY OF RUN-IN TO PLASMA TEMPERATURE AND RADIATION DURING 10-40NS "ASSEMBLY" TIME.

- CONVERSION OF KE MOSTLY TO TEMPERATURE

  MEANS LESS RADIATION OUT BUT HOTTER SPECTRUM OF RADIATION.

  CONVERSION OF KE MOSTLY TO RADIATION

  MEANS MORE RADIATION OUT BUT COLDER SPECTRUM.

IMPLODING PLASMA RADIATION SOURCES
HOW THEY WORK AND
WHY THEY'RE USEFUL

- PARALLEL CURRENT FLAMENTS ATTRACT EACH OTHER WITH A FORCE THAT IS STRONGER IF THE CURRENTS ARE LARGER OR THEIR SEPARATIONS SMALLER.

- EACH ELEMENT NEAR THE OUTER SURFACE OF AN ANNULAR HOLLOW PLASMA CYLINDER CARRIES CURRENT WHEN AN AXIAL ELECTRIC FIELD IS APPLIED FROM OUTSIDE THE CYLINDER.

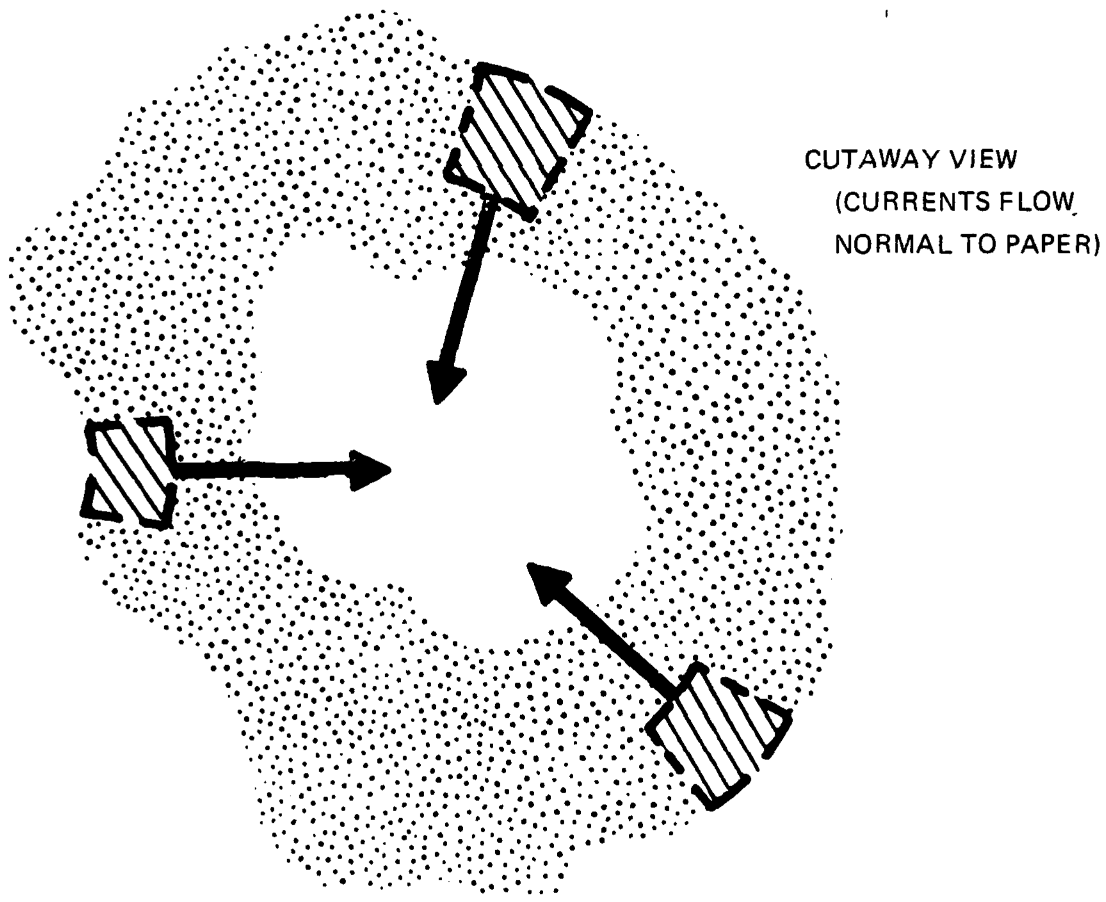


Fig. 1 — Forces on current filaments

- HOW MUCH CURRENT IS CARRIED DEPENDS ON:

    (1) HOW HOT THE PLASMA IS (MORE CURRENT IN HOTTER PLASMA, FOR A GIVEN FIELD)

    (2) HOW FAST THE PLASMA ELEMENTS ARE MOVING RADIALLY (LESS CURRENT IF MOVING INWARD FASTER)

THIS AFFECTS THE EFFICIENCY OF CONVERTING ELECTRIC FIELD ENERGY OUTSIDE THE PLASMA TO ENERGY OF MOTION OF THE PLASMA. (FIG. 2)

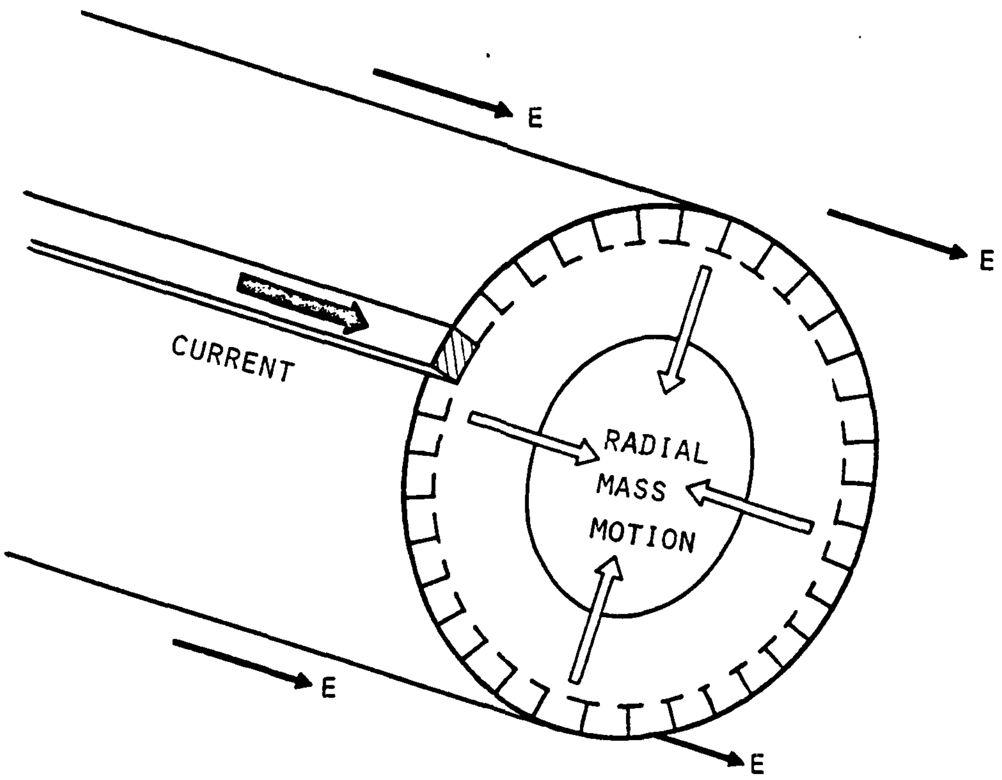


Fig. 2 — A typical plasma current filament (shaded), with current driven by external electric field E.

• THE ANNULAR CYLINDER OF PLASMA CONSTRICTS, AND ACQUIRES KINETIC ENERGY AS IT MOVES INWARD RADIALLY. (RUN-IN PHASE, FIG. 3)

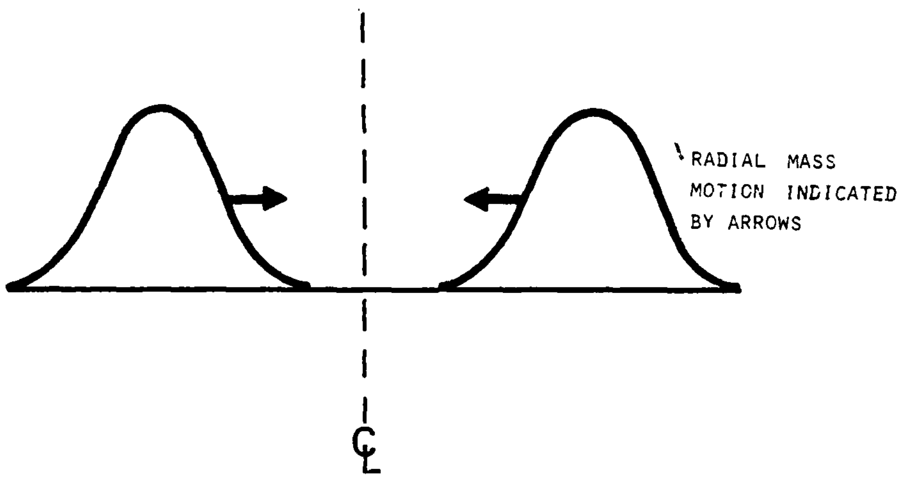


Fig. 3 — Plasma density vs radius

• EVENTUALLY THE IMPLODING HOLLOW PLASMA MEETS THE CENTER-LINE AND BECOMES A COMPRESSING NON-HOLLOW PLASMA (FIG. 4).

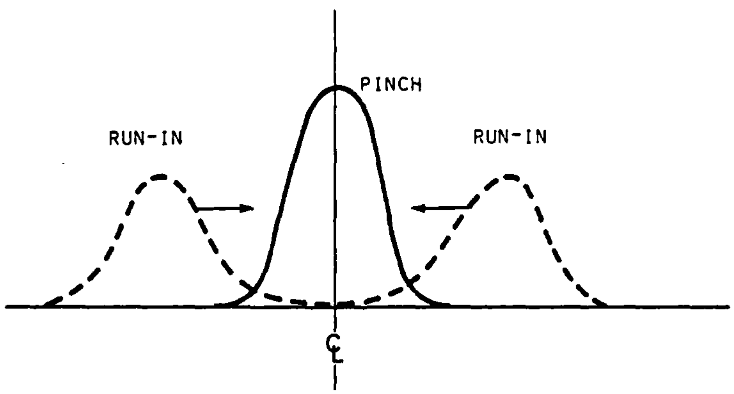


Fig. 4 — Density vs radius in the run-in phase (dashed) and pinch phase (solid)

- THE TIME REQUIRED TO GO FROM A HOLLOW PLASMA TO A NON-HOLLOW ONE IS USUALLY MUCH SHORTER THAN THE DURATION OF THE RUN-IN PHASE. DURING THIS SHORT TIME, MUCH OF THE KINETIC ENERGY OF RADIAL MOTION IS CONVERTED TO THERMAL ENERGY AND RADIATIVE POWER (FIG. 5).

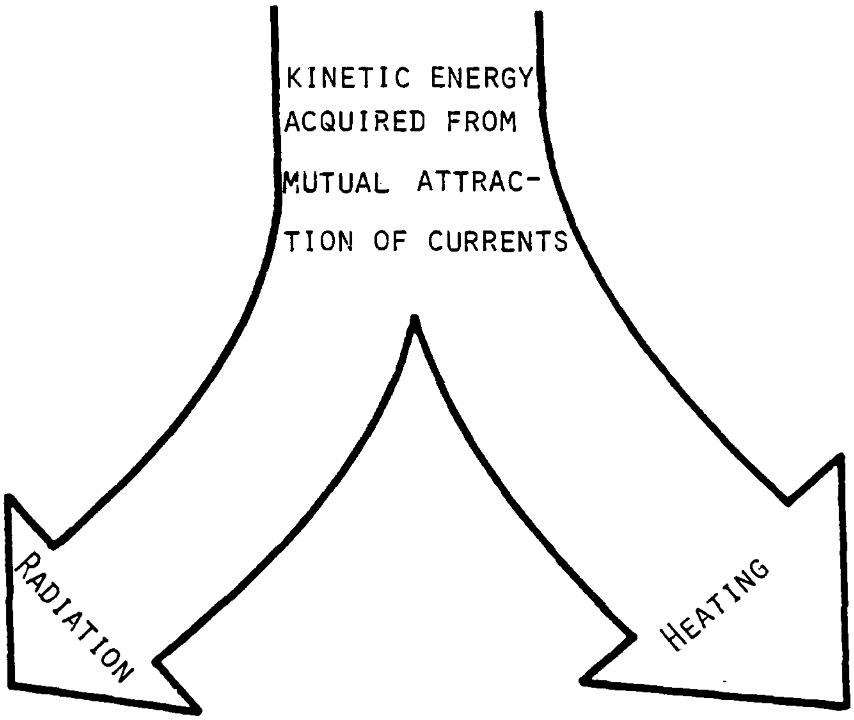


Fig. 5 — Energy flow into competing channels, with branching determined by density, temperature, and energy input rate.

- THE OUTERMOST PART OF THE PLASMA HAS ENOUGH INWARD INERTIA TO CONTINUE COMPRESSING THE PLASMA UNTIL THE THERMAL PRESSURE BECOMES LARGE ENOUGH TO REVERSE THE COMPRESSION.

- IF THERE WERE NO RADIATIVE OR OTHER ENERGY LOSS, THE COMPRESSED PLASMA WOULD EVENTUALLY SPRING OUTWARD AND RE-EXPAND (BOUNCE PHASE).

- RADIATIVE ENERGY LOSS PREVENTS THE TEMPERATURE FROM REACHING THE PEAK VALUE IT WOULD HAVE IF THERE WERE NO SUCH RADIATIVE COOLING.

- RADIATIVE COOLING THUS REDUCES THE VIGOR OF THE OUTWARD BOUNCE MOTION. IF RADIATIVE COOLING IS FAST ENOUGH, THERE IS NO BOUNCE.

- IF THE PLASMA TEMPERATURE AT THE TIME OF THE RADIATION IS HIGH ENOUGH, THE RADIATED ENERGY IS USEFUL BECAUSE ITS SPECTRUM IS ROUGHLY SIMILAR TO THAT OF A NUCLEAR DEVICE.

- THE RADIATION RATE IS AN INCREASING FUNCTION OF DENSITY, AND SO IT USUALLY PEAKS SHARPLY IN TIME NEAR THE TIME OF PEAK COMPRESSION OF THE PLASMA. THE RADIATION THUS COMES OUT LARGELY IN A SHARP PULSE OF SHORT DURATION AND HIGH POWER (FIG. 6).

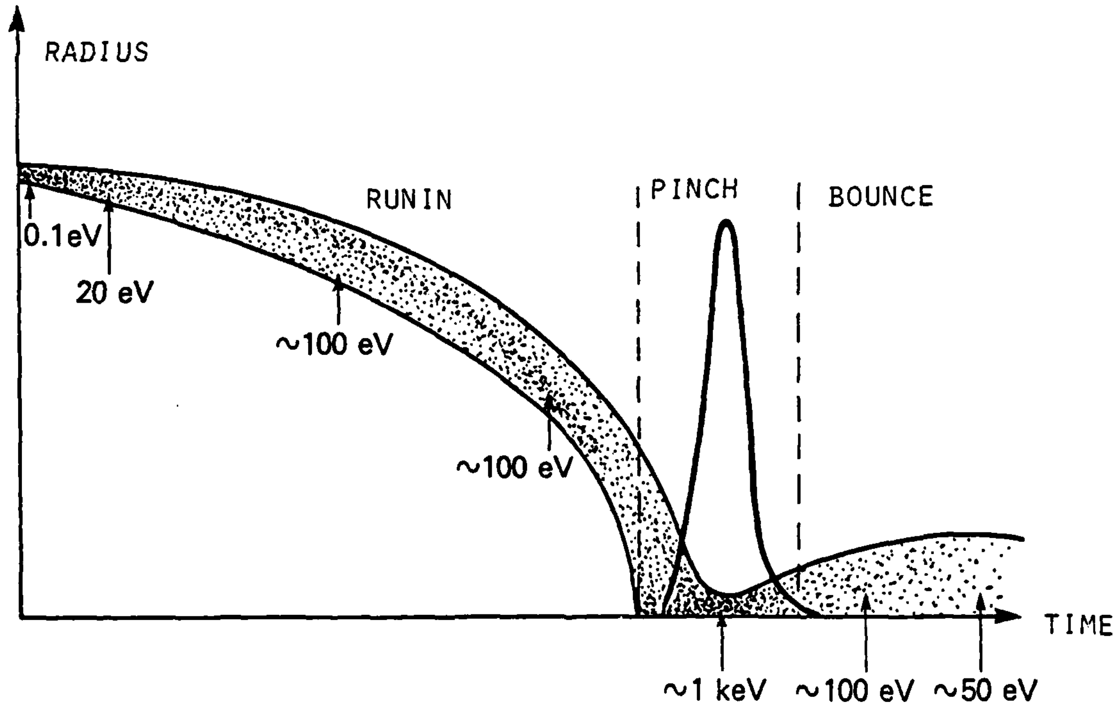


Figure 6

• FOR ANY DENSITY AND TEMPERTURE, THERE IS A SPECTRUM OF RADIATED PHOTON ENERGIES. ONLY THE HIGHER PHOTON ENERGIES ARE OF INTEREST FOR THE SIMULATION OF A NUCLEAR DEVICE, ALTHOUGH THE RADIATION AT LOWER PHOTON ENERGIES (THE 'COOLER' PART OF THE SPECTRUM) MAY HAVE IMPORTANT SIDE EFFECTS (FIG. 7).

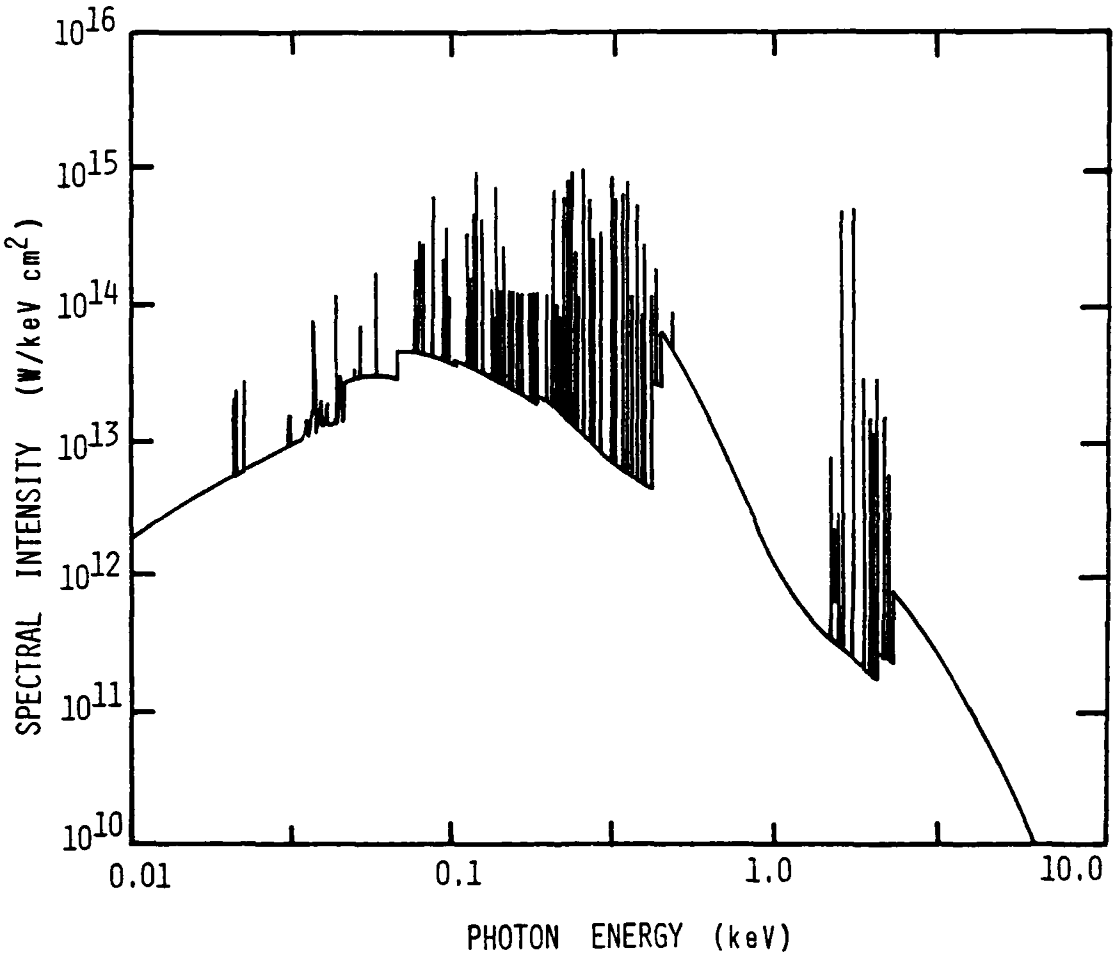


Figure 7

- THE RADIATED POWER IN HIGH-ENERGY PHOTONS, SAY ABOVE 1 KEV, IS ALSO A FUNCTION OF PLASMA ELECTRON TEMPERATURE. THIS FUNCTION USUALLY HAS A PEAK AT SOME OPTIMAL PLASMA ELECTRON TEMPERATURE, T_{PK} (FIG. 8). IF T IS FAR BELOW T_{PK}, FEW HIGH-ENERGY PHOTONS ARE RADIATED EVEN IF THE PLASMA DENSITY IS QUITE HIGH. THE SPECTRUM THEN IS SAID TO BE TOO COOL.

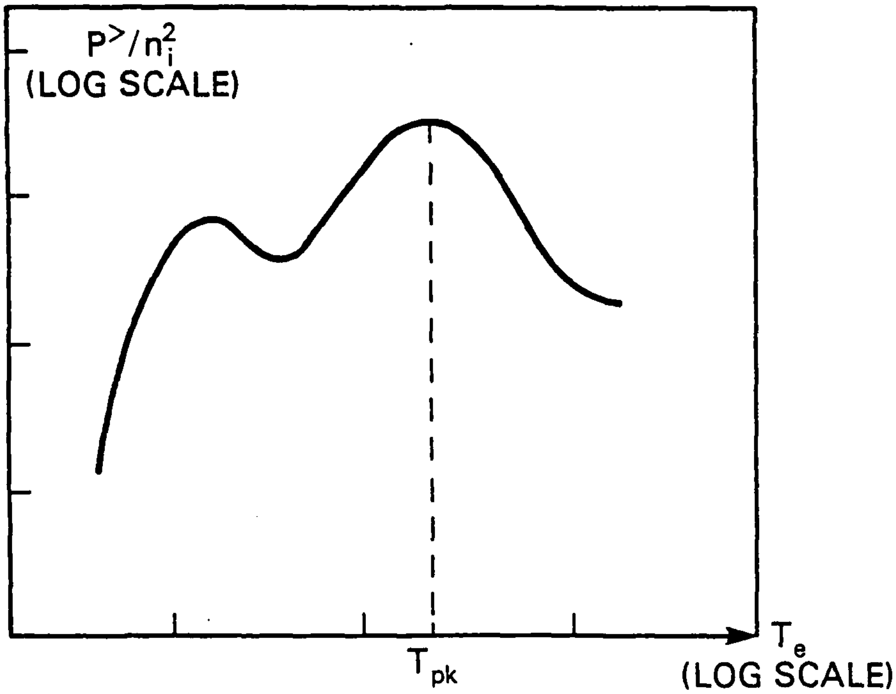


Fig. 8 — Radiated power above 1 keV photon energy per pair of ions, vs free electron temperature (includes increasing number of stripped electrons per ion as temperature increases). Note logarithmic scale.

- THE LONG RUN-IN TIME AND THE SUBSEQUENT SHORT PULSE-DURATION FOR THE ENERGETIC RADIATION MEAN THAT AN IMPLODING PLASMA CAN ABSORB ELECTROMAGNETIC FIELD ENERGY OVER THE RUN-IN TIME, OF ORDER 200 NS, AND TRANSFORM SOME OF THAT ENERGY INTO AN ENERGETIC RADIATION PULSE WITH DURATION OF ORDER 20 NS, IF IT GETS THE PLASMA HOT ENOUGH. THIS TIMESCALE SHORTENING IS USEFUL, SINCE IT WOULD BE DIFFICULT TO MAKE THE PLASMA ABSORB SO MUCH ENERGY ON THE DESIRED SHORTER TIMESCALE.

TIME HISTORY OF AN IMPLODING PLASMA DISCHARGE

- THE HISTORY OF AN IMPLODING PLASMA DISCHARGE DIVIDES INTO 5 PHASES:

1. EARLY-TIME DEVELOPMENT: THE FIRST CURRENT, PERHAPS A "PRE-PULSE", HEATS THE WIRES OR GAS OF THE DISCHARGE TO ~ 1 EV AND IONIZES IT.

2. THE PLASMA FATTENS FROM HEATING, AND BEGINS ITS ACCELERATION TOWARD THE AXIS.

3. THE DISCHARGE PLASMA ACCELERATES AT AN INCREASING RATE TOWARD THE AXIS AND ACHIEVES A HIGH RUN-IN VELOCITY (TYPICALLY ~ 4×10^7 CM/S) DURING THE LAST 30-60 NS OF ITS RUN-IN PHASE.

4. THE PLASMAS COLLIDE AND ASSEMBLE AT THE AXIS, CONVERTING THEIR RUN-IN ENERGY TO HEAT AND RADIATIVE LOSS (AND ADDITIONAL MAGNETIC FIELD ENERGY) AS THE ASSEMBLED PLASMA SELF-PINCHES.

5. LATE TIME PHASE: THE PINCH DISASSEMBLES (OFTEN PREDOMINANTLY IN AN UNSTABLE, INHOMOGENEOUS WAY) AND/OR COOLS RADIATIVELY AT HIGH DENSITY, UNTIL ITS RADIATION IS NO LONGER INTERESTING. THE ONLY HEAT SOURCE IN THIS STAGE IS OHMIC HEATING.

TO START WITH:
WIRES, FOILS, HOLLOW GAS PUFFS, OR ANNULAR METAL VAPOR PLASMAS?

- FOILS, ANNULAR METAL-VAPOR PLASMAS, AND GAS PUFFS ALL INITIALLY LOOK FAIRLY SYMMETRIC IN AZIMUTH (FIG. 9).

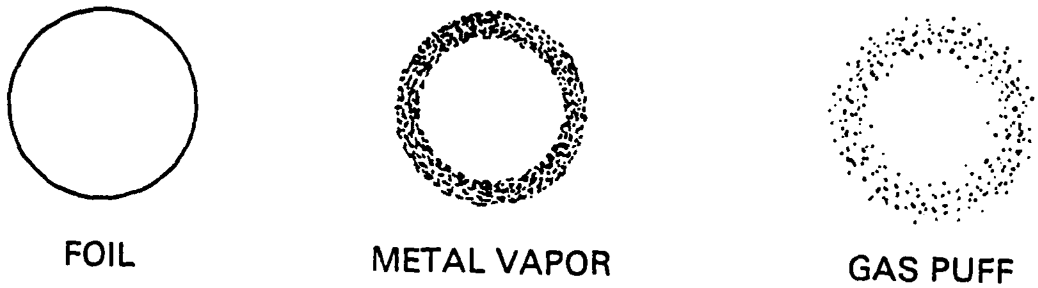


Figure 9

- WIRES HAVE AZIMUTHAL NONUNIFORMITY INITIALLY, AND ONLY AFTER THE WIRE PLASMAS RUN-IN AND COALESCE DOES ONE REACH NEAR-UNIFORMITY IN AZIMUTH (FIG. 10).

Figure 10

- Foils look initially more uniform axially (Fig. 11) than gas puffs or metal-vapor plasmas.

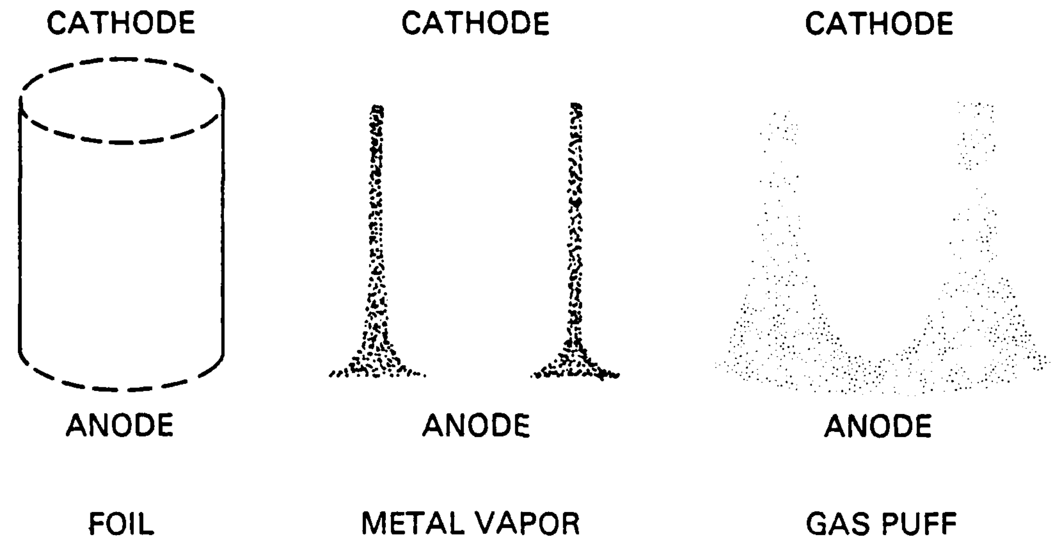


Figure 11

- Gas puffs are initially thicker than foils and can be made less massive (Fig. 12). Metal vapor plasmas probably will have intermediate initial thickness and mass.

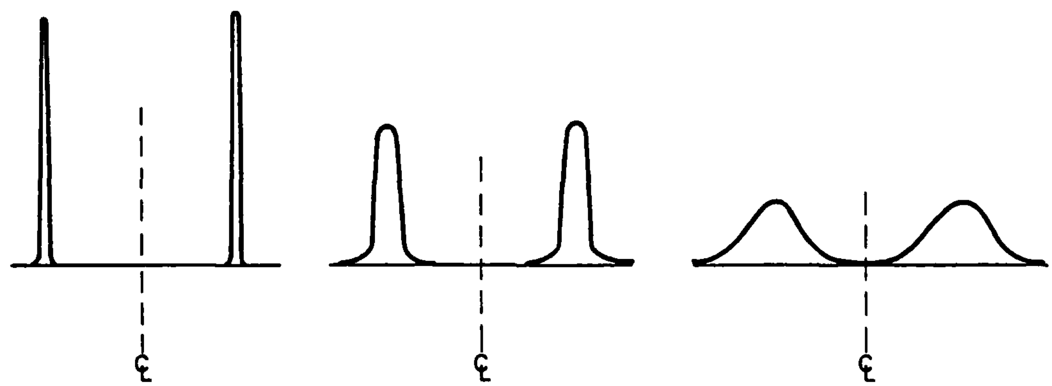


Fig. 12 — Initial density profiles for foil, metal plasma, and gas puff midway between anode and cathode.

- Higher Mach-number gas injection (faster injection) can give reduced axial flaring (Fig. 13) compared with lower Mach number.

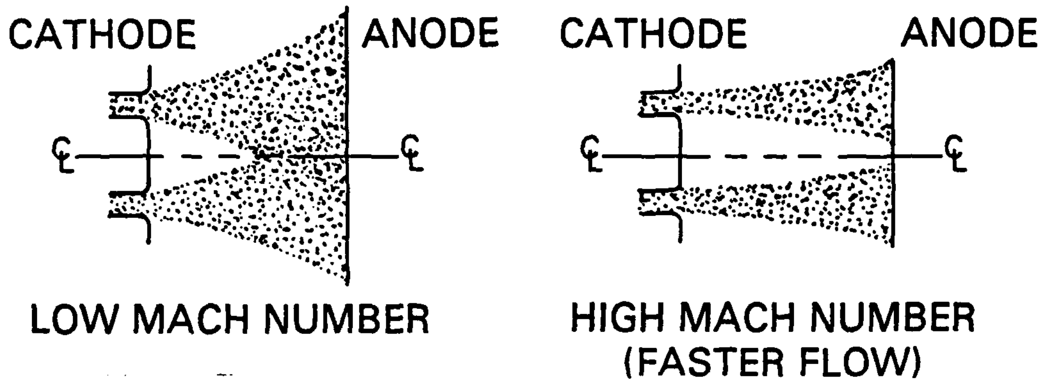


Figure 13

- Foils thick enough to work with have provided excessively large mass for best coupling to the earlier generators. Higher-current generators may couple better to foils of workable thickness in the future.

RADIATION GENERATION AND ABSORPTION - SIMPLEST APPROXIMATION

- RADIATION GENERATION RATE (WATTS/CM^2) AT EACH POINT IS

$$P_{RAD}^{TOT}\ (N,T),$$

A FUNCTION OF THE ION DENSITY N (IONS/CM^3) AND THE ELECTRON TEMPERATURE T (eV OR ^{o}K). THIS IS A SUM OVER ALL PHOTON ENERGIES.

- RADIATION ABSORPTION RATE (W/CM^3) AT EACH POINT IS

$$P_{ABS}^{TOT}\ (N,\ T).$$

THIS IS A SUM OF THE ABSORPTIONS AT ALL PHOTON ENERGIES - ABSORPTION DEPENDS VERY STRONGLY ON PHOTON ENERGY.

- ENERGETIC RADIATION (SUPERSCRIPT ">") IS GENERATED AT A RATE

$$P_{RAD}^{>}\ (N,T),$$

A DIFFERENT FUNCTION OF ION DENSITY N AND ELECTRON TEMPERATURE T. THIS IS A SUM OVER ONLY PHOTON ENERGIES CALLED "ENERGETIC".

- ABSORPTION OF ENERGETIC RADIATION CAN SOMETIMES BE NEGLECTED IF THE PLASMA DENSITY IS NOT TOO HIGH. BUT WHEN IT CAN'T BE NEGLECTED, ITS SUM OVER ALL ENERGETIC PHOTON ENERGIES IS DENOTED

$$P_{ABS}^{>}\ (N,T)$$

RADIATION FROM A UNIFORM PINCH

- SUPPOSE TEMPERATURE AND DENSITY DON'T VARY MUCH OVER THE RADIAL EXTENT OF THE PINCH AT ANY GIVEN INSTANT.

- THE <u>ENERGETIC</u> RADIATION <u>GENERATION</u> RATE IS PROPORTIONAL TO ION DENSITY SQUARED, TIMES A FUNCTION OF T (ELECTRON TEMPERATURE):

$$P^{>}_{RAD}\ (\text{WATTS/CM}^3) \propto N^2 G(T).$$

- THE AVERAGE DENSITY N VARIES INVERSELY AS THE SQUARE OF THE PINCH RADIUS,

$$N \propto 1/R^2,$$

BECAUSE THE SAME TOTAL NUMBER OF IONS ARE CONTAINED IN THE PINCH VOLUME $\pi R^2 \ell$ AS R CHANGES WITH TIME DURING PINCHING.

- THE VOLUME-INTEGRATED <u>ENERGETIC</u> RADIATION GENERATION IS

$$\mathbb{P}^{>}_{RAD}(\text{WATTS}) = \pi R^2 \ell \ P^{>}_{RAD},$$

WHICH VARIES AS $(1/R^2)\ G(T)$ SINCE $P^{>}_{RAD} \propto N^2 G(T)$ AND

$N^2 \propto 1/R^4$.

- BOTH R AND T CHANGE WITH TIME DURING THE PINCHING. T INCREASES BY COMPRESSIONAL HEATING AS R DECREASES. THIS IS ONLY PARTLY OFFSET BY RADIATIVE ENERGY-LOSS COOLING. IF RADIATIVE ENERGY LOSS IS SMALL, T RATHER STRICTLY FOLLOWS CHANGES IN R AND THE PINCH IS NEARLY "REVERSIBLE" OR "ADIABATIC", I.E. SYMMETRIC IN TIME.

- WHEN RADIATIVE ENERGY LOSS IS NOT NEGLIBIBLE, THE SAME VALUE OF R AFTER PINCHING WILL HAVE A COOLER T THAN BEFORE PINCHING, AND R WILL NOT SPRING BACK AS FAR (FIG. 14). THIS IS THE "NONADIABATIC" PINCH.

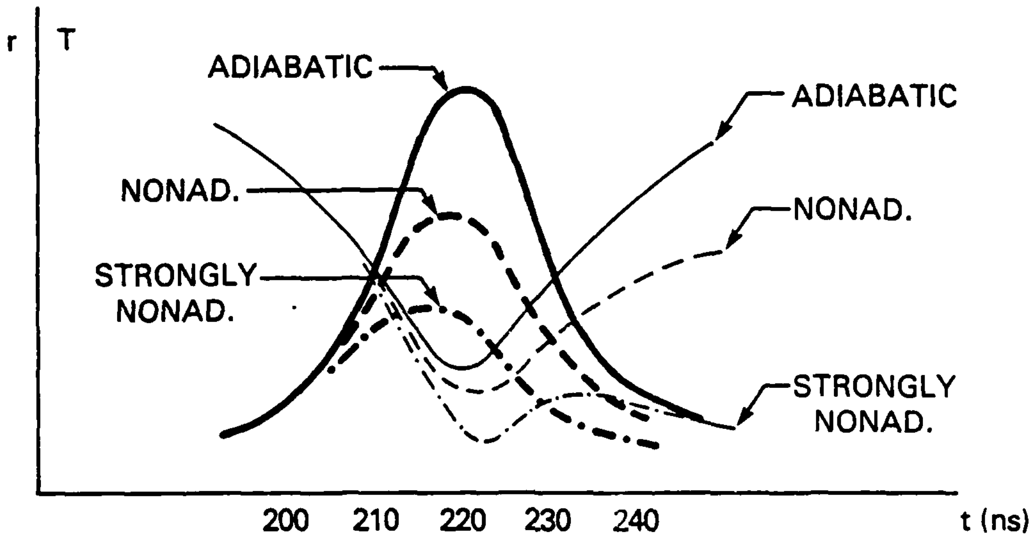


Fig. 14 — Radius and temperature vs time near peak pinch compression

- THE <u>TOTAL</u> RADIATIVE <u>YIELD</u> FROM A PINCH IS THE TIME-INTEGRAL OF THE <u>TOTAL NET</u> RADIATED POWER (POWER PER CM^3 INTEGRATED OVER VOLUME AND PHOTON ENERGIES)

$$Y_{TOT} = \int DT \left(\mathbb{P}^{TOT}_{RAD} - \mathbb{P}^{TOT}_{ABS} \right)$$

$$= \int DT \, \pi R^2 \ell \, (P^{TOT}_{RAD} - P^{TOT}_{ABS})$$

- THE <u>ENERGETIC</u> RADIATIVE <u>YIELD</u>, SIMILARLY, IS THE TIME-INTEGRAL OF THE <u>ENERGETIC NET</u> RADIATED POWER (NET MEANS GENERATED POWER LESS ABSORBED POWER) - INTEGRATED ONLY OVER THOSE PHOTON ENERGIES CALLED "ENERGETIC":

$$Y^{>} = \int DT \, (\mathbb{P}^{>}_{RAD} - \mathbb{P}^{>}_{ABS})$$

IMPLODING PLASMA AS A CIRCUIT ELEMENT

- THE PLASMA CARRIES A TIME-DEPENDENT CURRENT IN RESPONSE TO A TIME-DEPENDENT DRIVING VOLTAGE SET UP AS AN IMPINGING ELECTROMAGNETIC PULSE.

- THE PLASMA HAS A RESISTANCE AND A SELF-INDUCTANCE; BOTH ARE TIME-VARYING.

- THE RESISTIVITY DECREASES AS THE PLASMA HEATS UP. THE PLASMA CONDUCTIVITY $\sigma \propto T^{3/2}/Z(T)$, WHERE THE DEGREE OF IONIZATION $Z(T)$ INCREASES TOWARDS COMPLETE IONIZATION (BARE NUCLEI) AS THE TEMPERATURE T RISES.

- THE CURRENT IS PROBABLY NOT CARRIED UNIFORMLY IN THE PLASMA, BUT IN A "SKIN CURRENT" LAYER OF THICKNESS δ AND CROSS-SECTION AREA $A_{CURR} \sim 2\pi R\delta$. THE THICKNESS δ WOULD INCREASE WITH TIME BY "MAGNETIC DIFFUSION" IF THE SURFACE WERE NOT MASHED BY THE ELECTRODYNAMIC FORCES OF ITS OWN CURRENTS.

- THE INTRINSIC PLASMA RESISTANCE IS $R_P = \ell/(\sigma\, A_{CURR})$, WITH ℓ THE PLASMA COLUMN LENGTH. TYPICALLY ONE EXPECTS $\sim .5$ OHM PER CM OF LENGTH FOR COOL PLASMA, DECREASING TO TYPICALLY .01 OHM/CM WHEN T GETS TO THE KEV RANGE.

- JUST AS EVASION CAN LOOK LIKE RESISTANCE, THERE IS ANOTHER "EFFECTIVE RESISTANCE" DUE TO TIME-VARIATION OF THE INDUCTANCE, AS THE IMPLODING PLASMA "MOVES OUT OF THE WAY" OF THE SURROUNDING HIGH-FIELD REGION. THIS IS DISCUSSED IN A MOMENT. THIS "EFFECTIVE RESISTANCE" CAN BE ONE OR MORE OHMS, FOR TYPICAL PEAK IMPLOSION SPEEDS, AND SO IT CAN BE LARGER THAN THE INTRINSIC PLASMA RESISTANCE.

- THE SELF-INDUCTANCE OF AN ANNULAR CURRENT-CARRYING LAYER IS A GEOMETRICAL PROPERTY OF THE LAYER:

$$L_p \text{ (HENRIES)} = 2\times10^{-9}\ell(\text{CM})\ln(R_W/R)$$

FOR A THIN LAYER ($\delta \ll R$) OF LENGTH ℓ. AND RADIUS R INSIDE A CYLINDRICAL CAVITY OF RADIUS R_W.

- THE RATE OF CHANGE OF L_p WITH TIME IS THE MOTIONAL PART OF THE EFFECTIVE RESISTANCE:

$$\dot{L}_p \text{ (OHMS)} = -2\times10^{-9}\ \ell(\text{CM})\ \dot{R}(\text{CM/S})/R(\text{CM})$$

FOR A THIN LAYER. (THE DOT WILL ALWAYS INDICATE TIME DERIVATIVE.)

- $\dot{L}_p$ IS CLEARLY LARGER WHEN THE IMPLOSION SPEED $|\dot{R}|$ IS LARGER.

- THE EQUIVALENT CIRCUIT IS, TO A GOOD APPROXIMATION (FIG. 15).

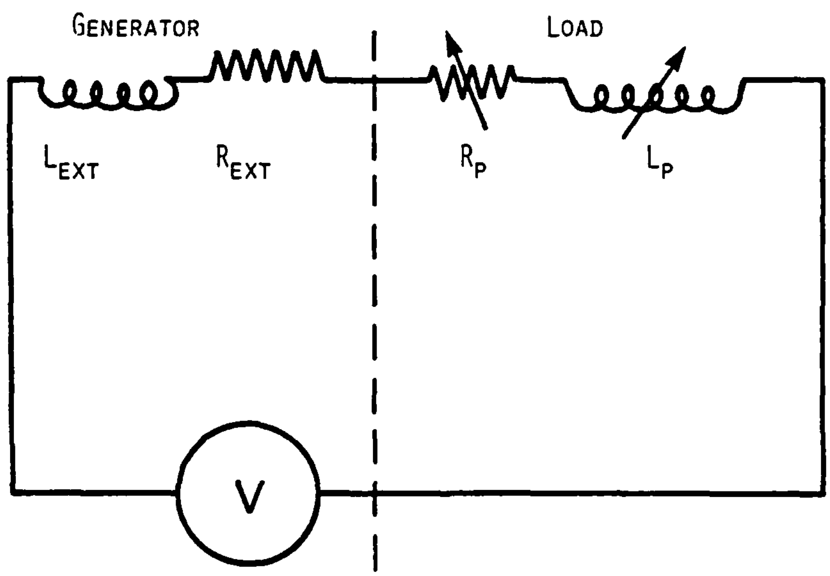


Figure 15

- THE CURRENT, I, THROUGH THE PLASMA LOAD IS GIVEN BY THE CIRCUIT EQUATION

$$(R_P + R_{EXT} + \dot{L}_P)\, I + (L_P + L_{EXT})\, \dot{I} = V$$

WHERE V IS THE TIME VARYING VOLTAGE,

R_{EXT} IS ANY EXTERNAL RESISTANCE IN SERIES WITH THE LOAD
L_{EXT} IS THE EXTERNAL MACHINE INDUCTANCE, IN SERIES WITH THE LOAD.

SHOCK DURING RUN-IN

- WHEN THE SELF-PINCHING FORCE ON THE PLASMA RISES RAPIDLY, THE OUTER PART OF THE PLASMA IS MASHED (INCREASING ITS DENSITY) AND THIS COMPRESSION MOVES RADIALLY INTO THE REST OF THE PLASMA AS A SHOCK WAVE.

- RADIATIVE ENERGY TRANSPORT FROM THE HOT COMPRESSED SHOCK REGION TO THE COOLER UNSHOCKED PLASMA TENDS TO HELP DAMP OUT THE SHOCK. A RADIATION MODEL IS THUS IMPORTANT IN FINDING OUT WHETHER SUCH A SHOCK IS DAMPED OR REACHES THE INNER SURFACE OF THE PLASMA.

IF THE SHOCK REACHES THE INNER SURFACE OF THE ANNULAR PLASMA, IT MAY "SPALL OFF" SOME OF THE PLASMA THERE, BLOWING IT TOWARD THE AXIS AT A HIGHER SPEED THAN THE BULK PLASMA MOTION. (FIG. 16).

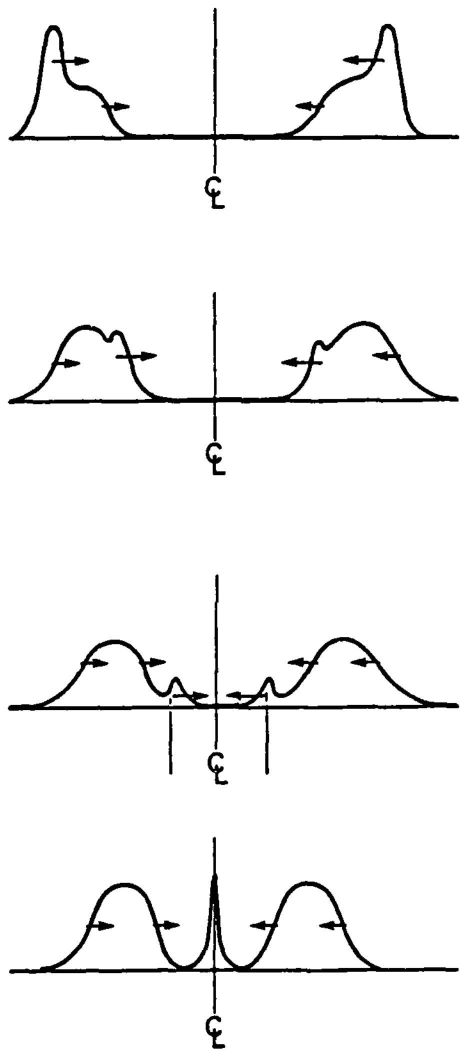


Fig. 16 — Inner surface "spall" by shock: end-on view of density profiles

- A SHOCK COULD THUS LEAD TO:

(A) RADIATION FROM THE SHOCK REGION, LONG BEFORE CLOSURE OF THE ANNULAR PLASMA, I.E. LONG BEFORE THE RADIATION PULSE OF THE PINCH PHASE, AND

(B) EARLY ASSEMBLY OF THE INNER-SURFACE BLOWOFF PLASMA AS IT REACHES THE AXIS BEFORE THE REST OF THE PLASMA DOES.

(C) A SPIKE OF RADIATION FROM THIS PREMATURE ASSEMBLING ON THE AXIS - RADIATION INCIDENT ON THE INCOMING ANNULAR PLASMA FROM THE *INSIDE*.

(D) SOME PREHEATING OF THE ANNULAR PLASMA IF IT ABSORBS ENOUGH OF THE RADIATION FROM THE CENTER.

ENERGY CONVERION IN PLASMA IMPLOSION (FIG. 17)

RUNIN PHASE:

EM ENERGY CONVERTED TO KINETIC ENERGY WITH SOME SMALL OHMIC HEATING AND RADIATIVE COOLING.

SOME NEW EM ENERGY IS STORED IN THE INCREASING EMPTY VOLUME OUTSIDE THE SHRINKING PLASMA.

PINCH PHASE:

KINETIC ENERGY AQUIRED DURING RUN-IN IS TRANSFORMED TO TEMPERATURE, I.E. THERMAL STORAGE (INTERNAL ENERGY) AND TO RADIATION OUTPUT POWER. THE BRANCHING BETWEEN THESE TWO MODES (HOW MUCH HEATING VS HOW MUCH RADIATIVE LOSS) IS A COMPLICATED NONLINEAR FUNCTION OF DENSITIES, TEMPERATURES, ASSEMBLY TIMESCALE, ETC.

CONVERSION OF KE MOSTLY TO INTERNAL ENERGY (THERMAL & IONIZATION) MEANS LESS RADIATION OUT BUT HOTTER SPECTRUM OF RADIATION.

CONVERSION OF KE MOSTLY TO RADIATION MEANS MORE RADIATION BUT WITH COLDER SPECTUM.

PLASMA NONUNIFORMITY (E.G. FROM INSTABILITIES) MAY MAKE FOR EFFICIENT RADIATION IN SOME REGIONS AND FOR THERMAL ENERGY FLOWING INTO THOSE REGIONS FROM NEIGHBORING REGIONS.

DISASSEMBLY PHASE:

REMAINING INTERNAL ENERGY IS CONVERTED BACK TO KINETIC ENERGY OF "BOUNCE" (I.E. TO RE-EXPANSION OF PLASMA), TO FURTHER RADIATION, AND TO ELECTROMAGNETIC WORK BACK ON THE GENERATOR. IF RADIATION COOLING IS FAST ENOUGH, THERE IS NO APPRECIABLE "BOUNCE". IF THE PLASMA IS UNSTABLE, IT MAY DISASSEMBLE VERY NONUNIFORMLY.

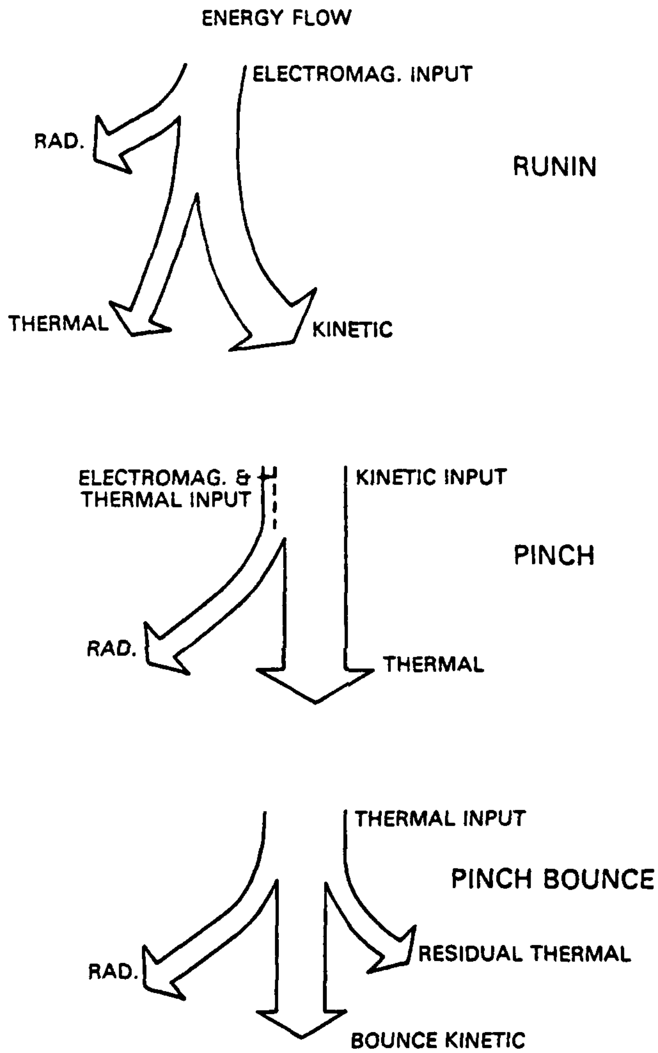
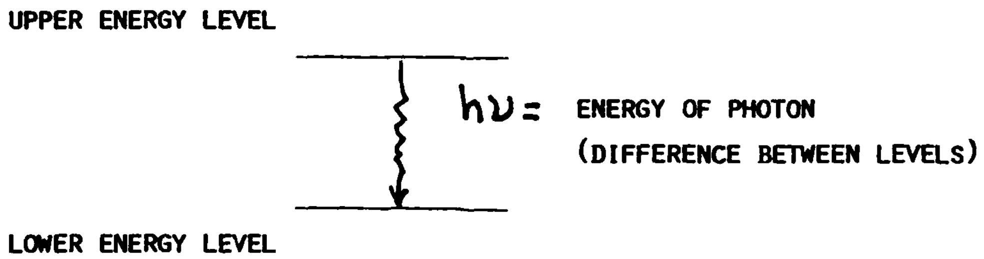

ENERGY FLOW
ELECTROMAG. INPUT
RAD.
RUNIN
THERMAL
KINETIC
ELECTROMAG. &
THERMAL INPUT
KINETIC INPUT
PINCH
RAD.
THERMAL
THERMAL INPUT
PINCH BOUNCE
RESIDUAL THERMAL
RAD.
BOUNCE KINETIC

Figure 17

How Can One Use Spectrum to Infer Plasma Properties?

A HOT PLASMA EMITS PHOTONS DUE TO:

1. LINE RADIATION, FROM QUANTUM TRANSITIONS OF IONS BETWEEN DIFFERENT DISCRETE ENERGY STATES



IN MOST PLASMAS THAT ARE NOT COMPLETELY "STRIPPED" I.E. WHERE THE IONS ARE NOT STRIPPED COMPLETELY BARE OF ELECTRONS BY THE THERMAL AGITATION, THIS IS THE DOMINANT FORM OF RADIATED SPECTRUM.

2. "FREE-BOUND" RADIATION, FROM TRANSITIONS BETWEEN "CONTINUUM" ENERGIES (ABOVE THE ION'S DISCRETE LEVELS) AND THE DISCRETE ENERGY LEVELS. THE SPECTRUM OF THIS RADIATION IS A CONTINUUM; HOWEVER THERE IS SOME STRUCTURE DUE TO THE DISCRETE NATURE OF THE LOWER ENERGY LEVELS.

3. "FREE-FREE" OR BREMSSTRAHLUNG RADIATION IS CAUSED BY THE ACCELERATION OF CHARGED PARTICLES IN THE COULOMB FIELD OF OTHER CHARGED PARTICLES. THE MAJOR PART OF THE BREMSSTRAHLUNG IS DUE TO THE ELECTRON-ION COLLISIONS AND SINCE THE INITIAL AND FINAL STATES ARE CONTINUOUS, THE BREMSSTRAHLUNG SPECTRUM IS ALSO CONTINUOUS.

- THE LINE RADIATION POWER IS THE SUM OF THE NET EMITTED POWERS FOR ALL THE POSSIBLE TRANSITIONS BETWEEN STATES OF ALL THE AVAILABLE IONS (E.G. IONS OF CHARGE 1,2,3,4,...., WEIGHTED BY THEIR POPULATION DENSITIES). THIS MAKES IT A COMPLICATED FUNCTION OF TEMPERATURE, IN PART BECAUSE THE POPULATION DENSITIES DEPEND ON TEMPERATURE, AND ALSO BECAUSE THE "OSCILLATOR STRENGTHS" OR EMISSION RATES OF EACH OF THE TRANSITIONS DEPENDS IN A QUANTUM-MECHANICAL WAY ON THE NATURE OF THE TRANSITION.

- TYPICALLY, THERE IS A DISTRIBUTION OF IONIZATION STATES FOR A FIXED DENSITY AT ANY TEMPERATURE AND, FOR A FIXED DENSITY, THE CENTER OF THE BAND MOVES TO HIGHER IONIZATION STAGES AS THE TEMPERATURE INCREASES, UNTIL FINALLY THE IONS ARE ALL, OR ALMOST ALL, COMPLETELY STRIPPED.

- THE WIDTH OF THE BAND OVER WHICH A GIVEN IONIZATION STAGE EXISTS DEPENDS ON THE SHELL STRUCTURE, IONIZATION ENERGY, ETC., I.E., ON ATOMIC FACTORS.

- FREE-BOUND RADIATION POWER ALSO HAS A NON-SIMPLE DEPENDENCE ON TEMPERATURE, BECAUSE OF THE CHANGING OF IONIZATION-STATE POPULATIONS WITH TEMPERATURE.

- FROM THE INTENSITY RATIO OF SELECTED SPECTRAL LINES IT IS POSSIBLE TO INFER SUCH PLASMA PROPERTIES AS ELECTRON TEMPERATURE AND DENSITY.

- FROM THE SLOPE OF THE FREE-FREE CONTINUUM IT IS POSSIBLE TO INFER THE ELECTRON TEMPERATURE FROM EITHER A THERMAL OR NONTHERMAL ELECTRON DISTRIBUTION.

- Clean measurements of spectral line profiles along with observable shifts and widths can also provide useful estimates of temperature and density.

- Another estimate of electron density can be obtained from high resolution high quality spectra by employing the last observable member of a line spectrum and with the aid of the Ingliss-Teller formalism unfold the density.

The determination of plasma parameters is such a rapidly expanding field we refer the reader to the current literature. The few diagnostic aids presented here are the time-honored "dependable" methods.

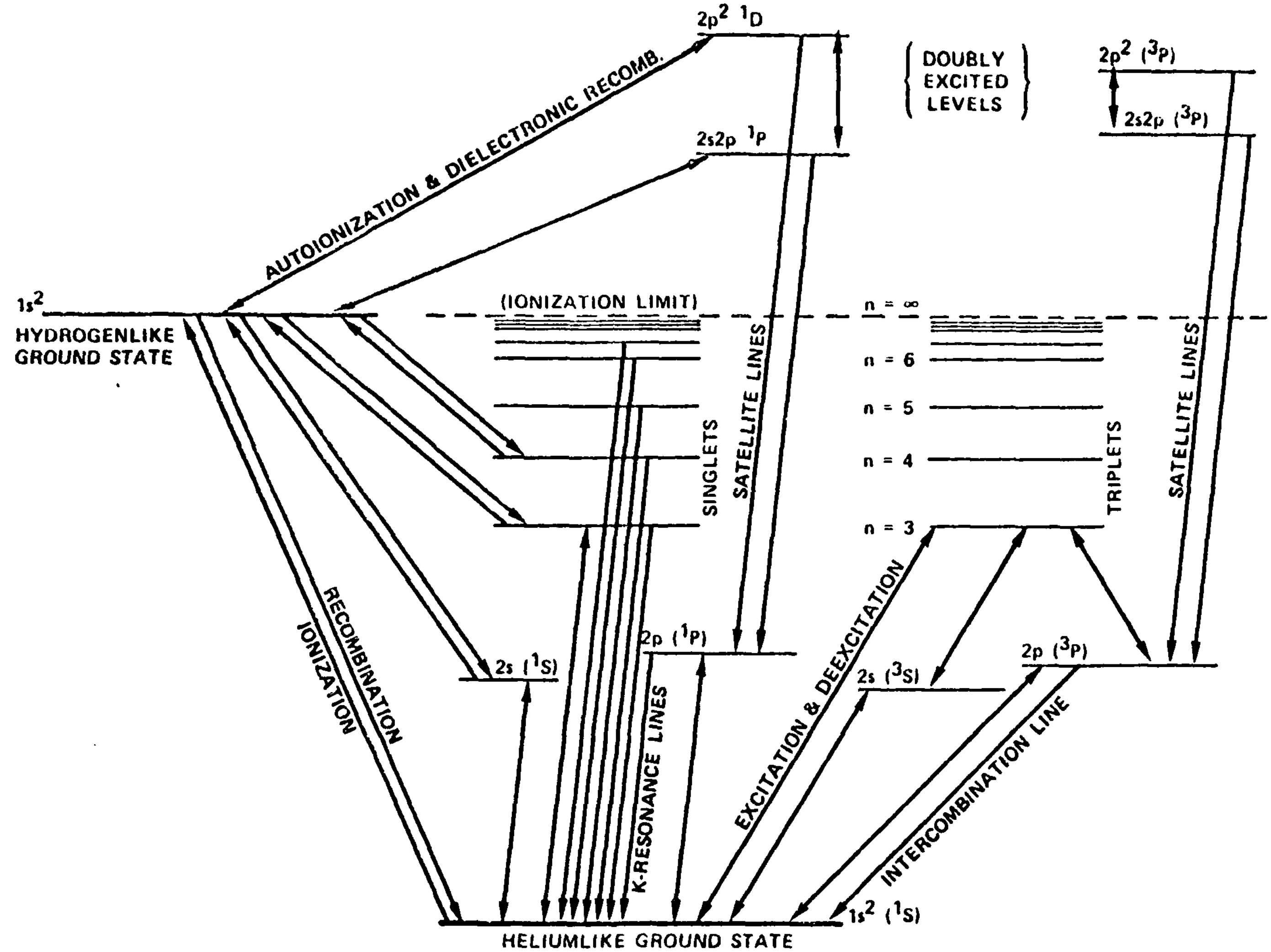


Fig. 18 — Typical energy level diagram, atomic processes and line emissions.

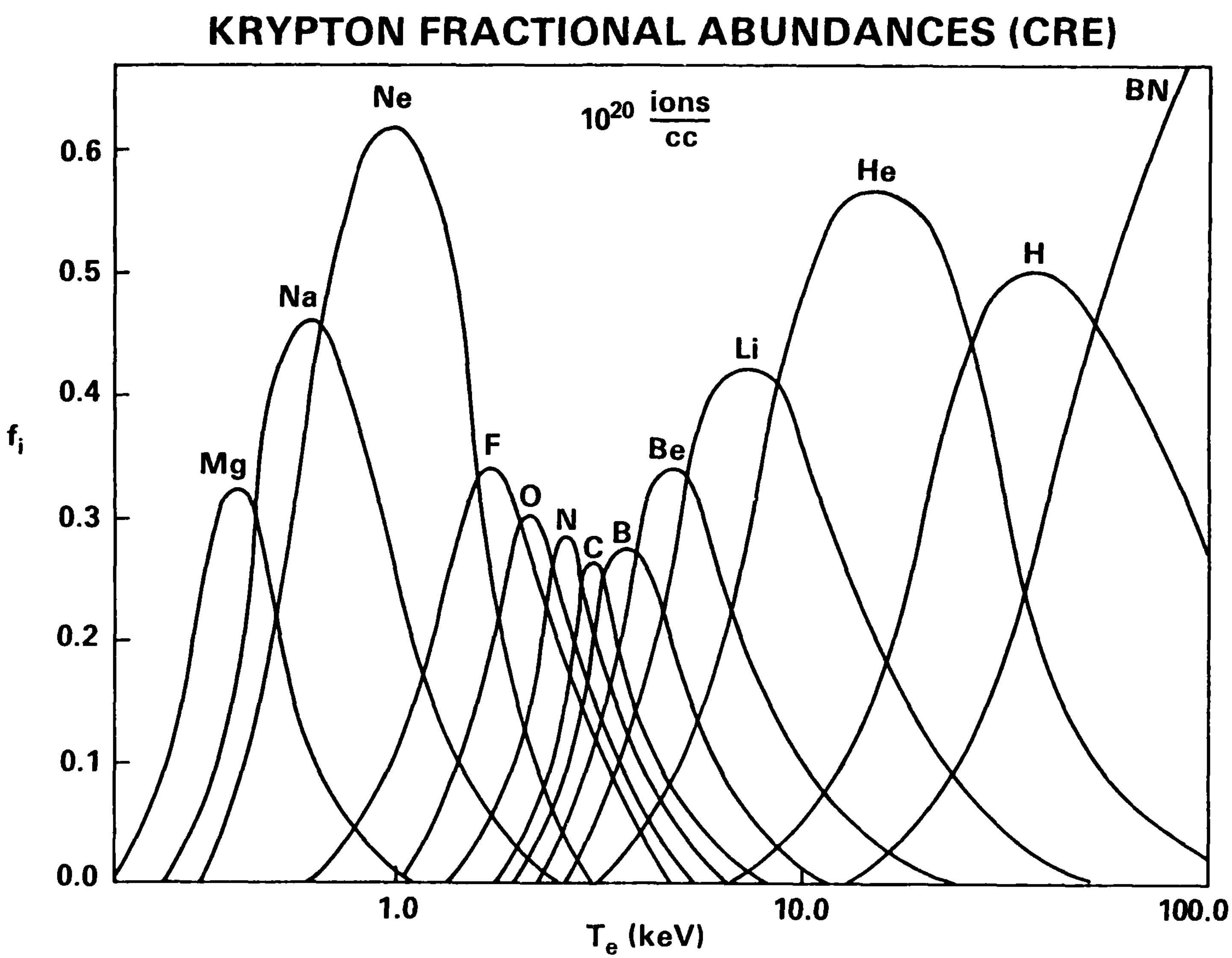


Fig. 19 — Distribution of ionization states for an optically thin krypton plasma

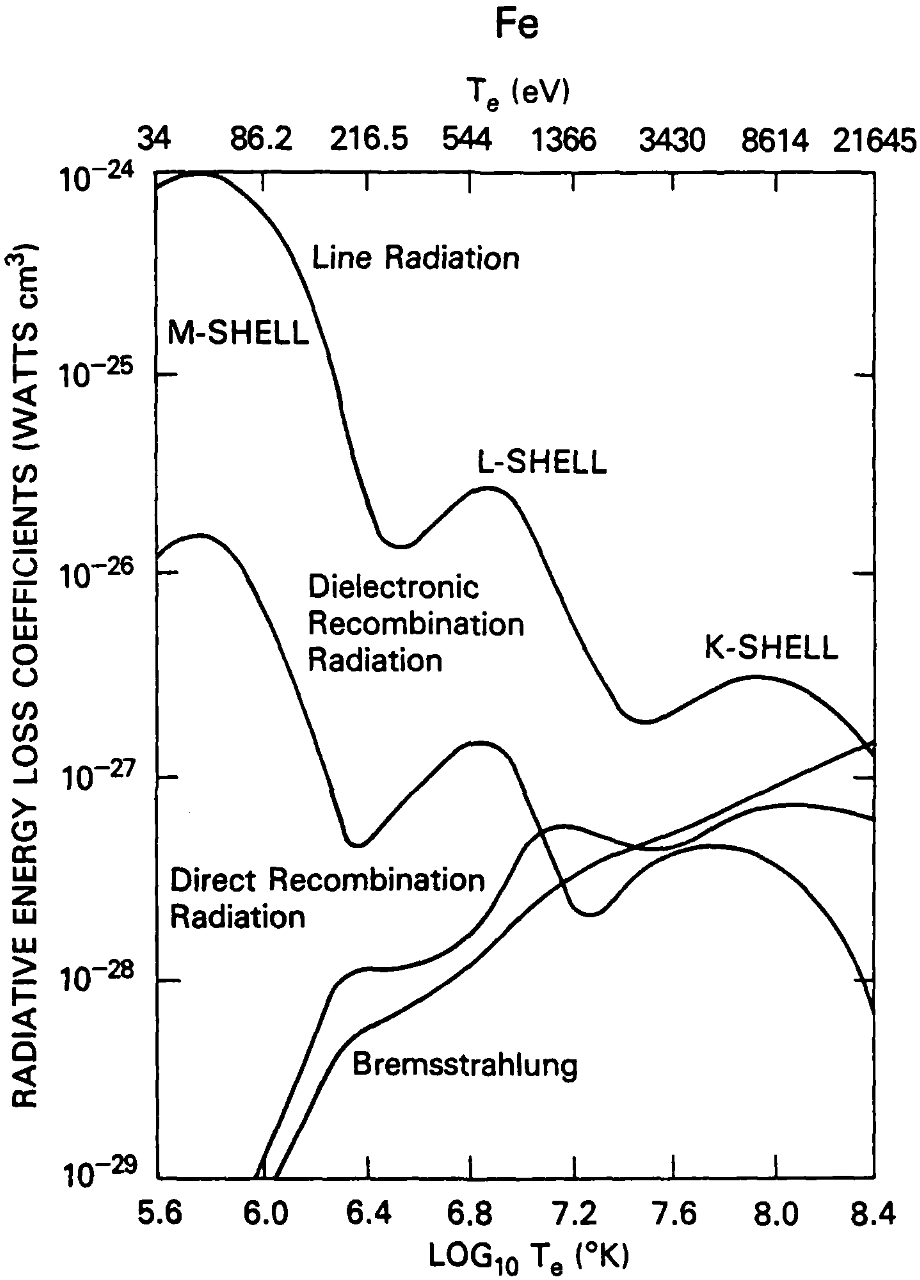


Fig. 20 — Radiative loss terms for a low density optically thin plasma

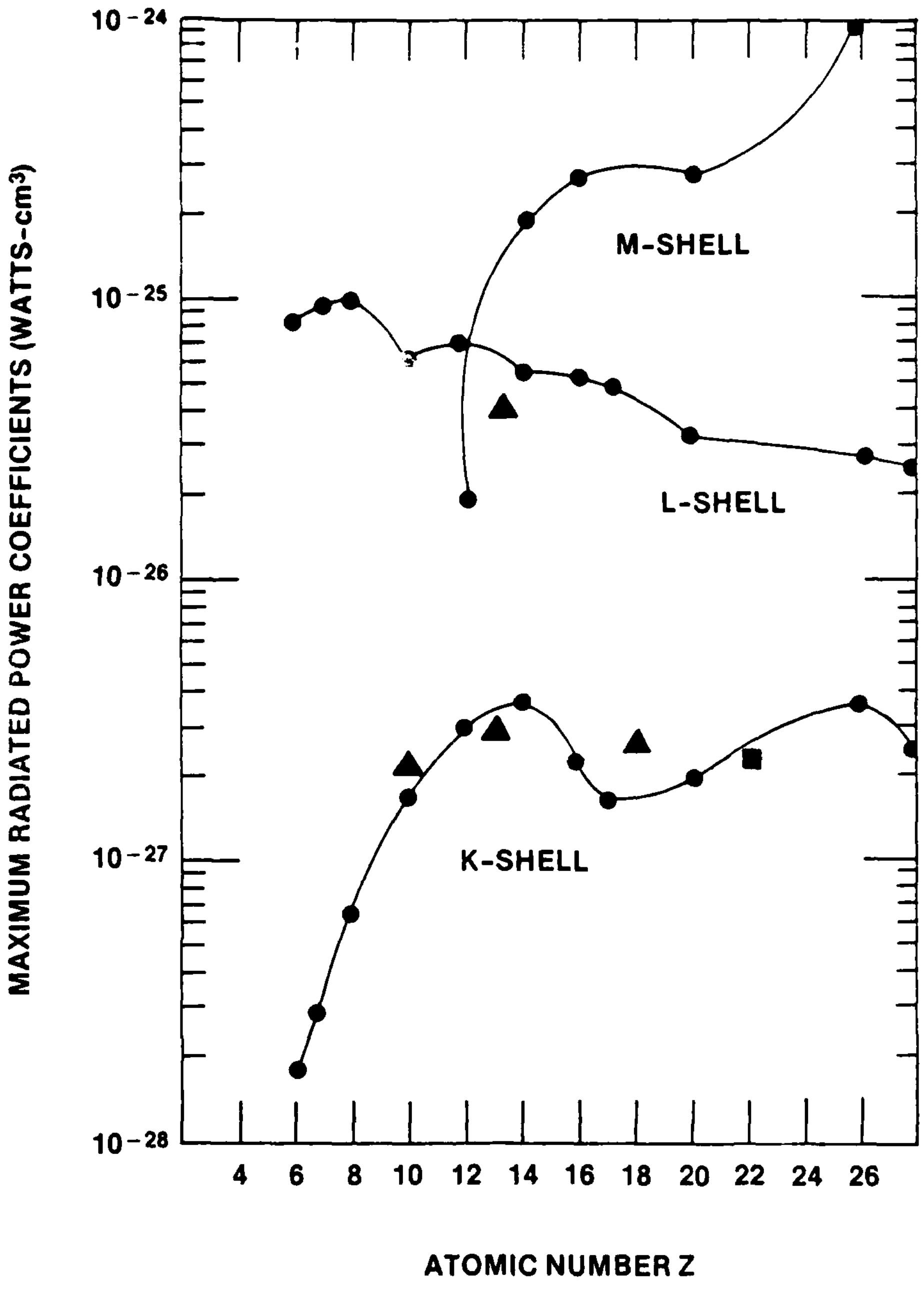
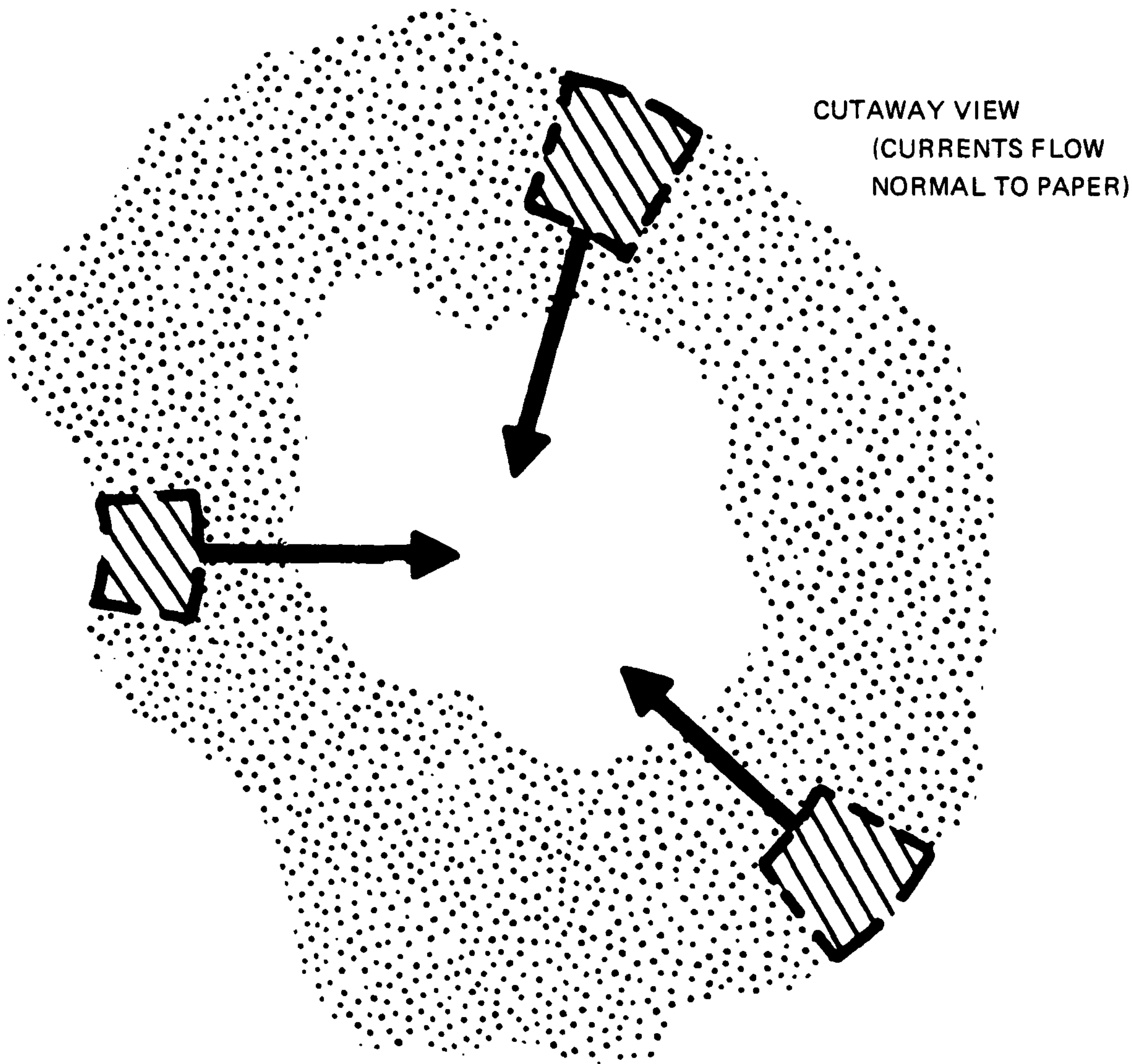
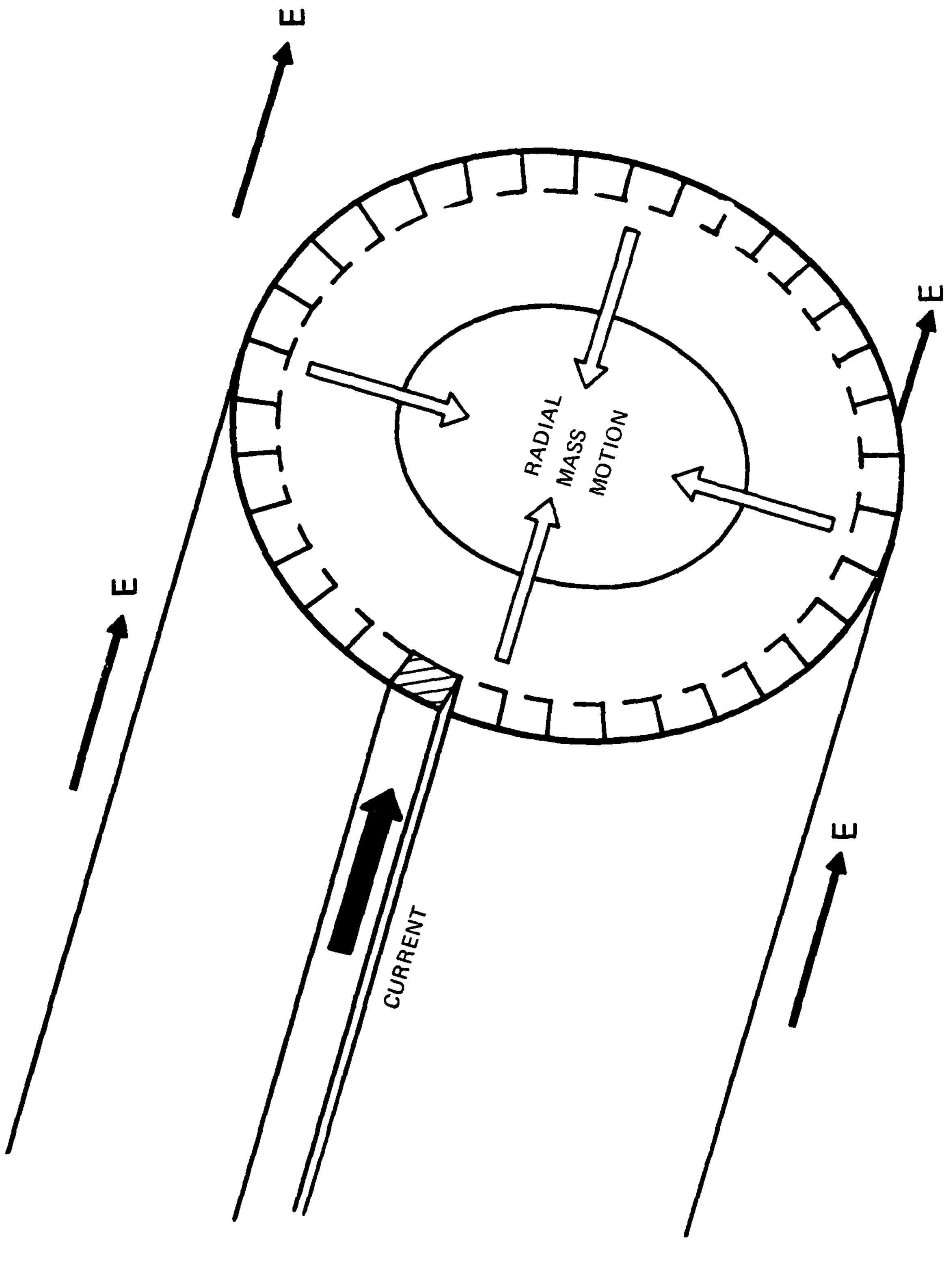
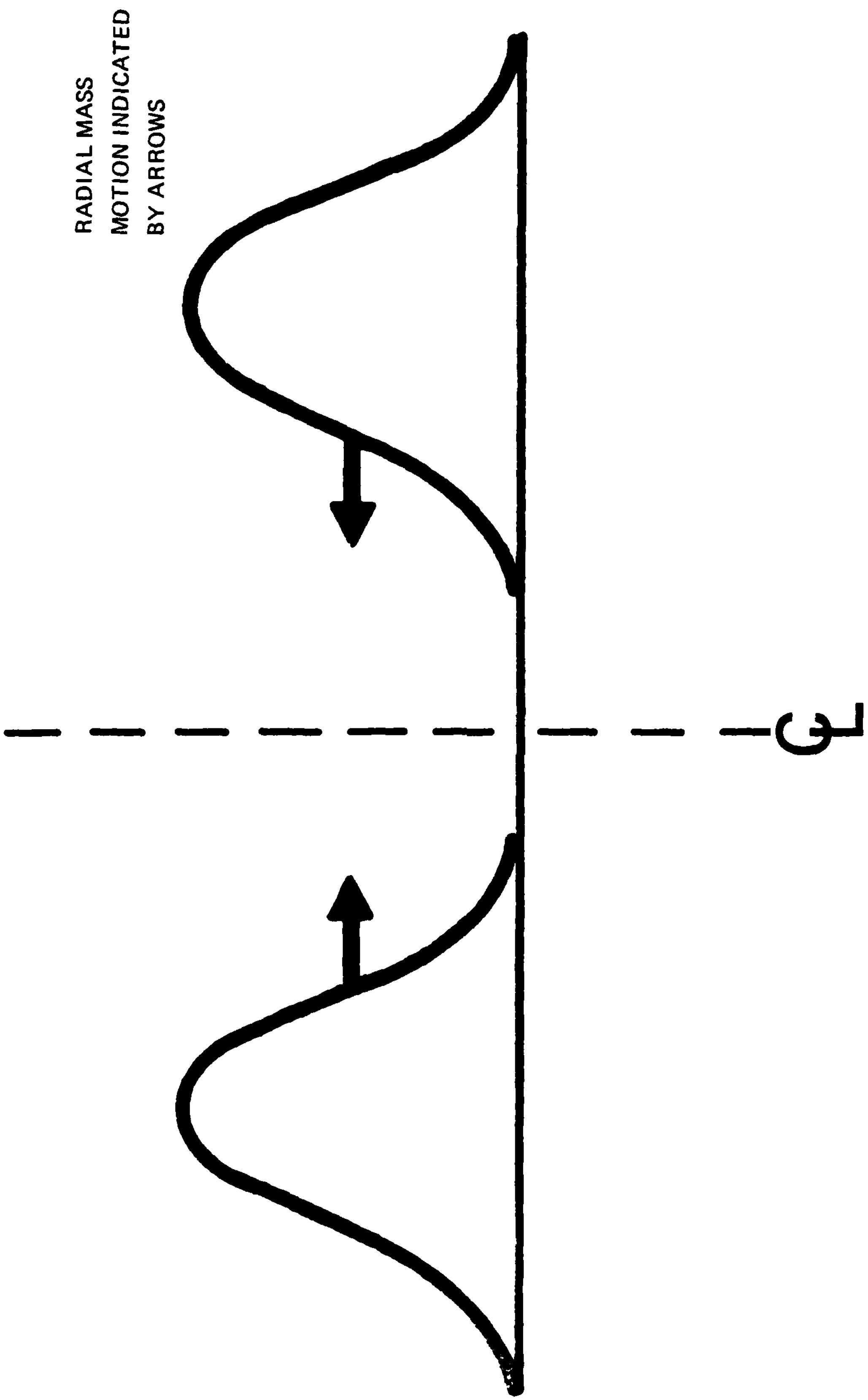
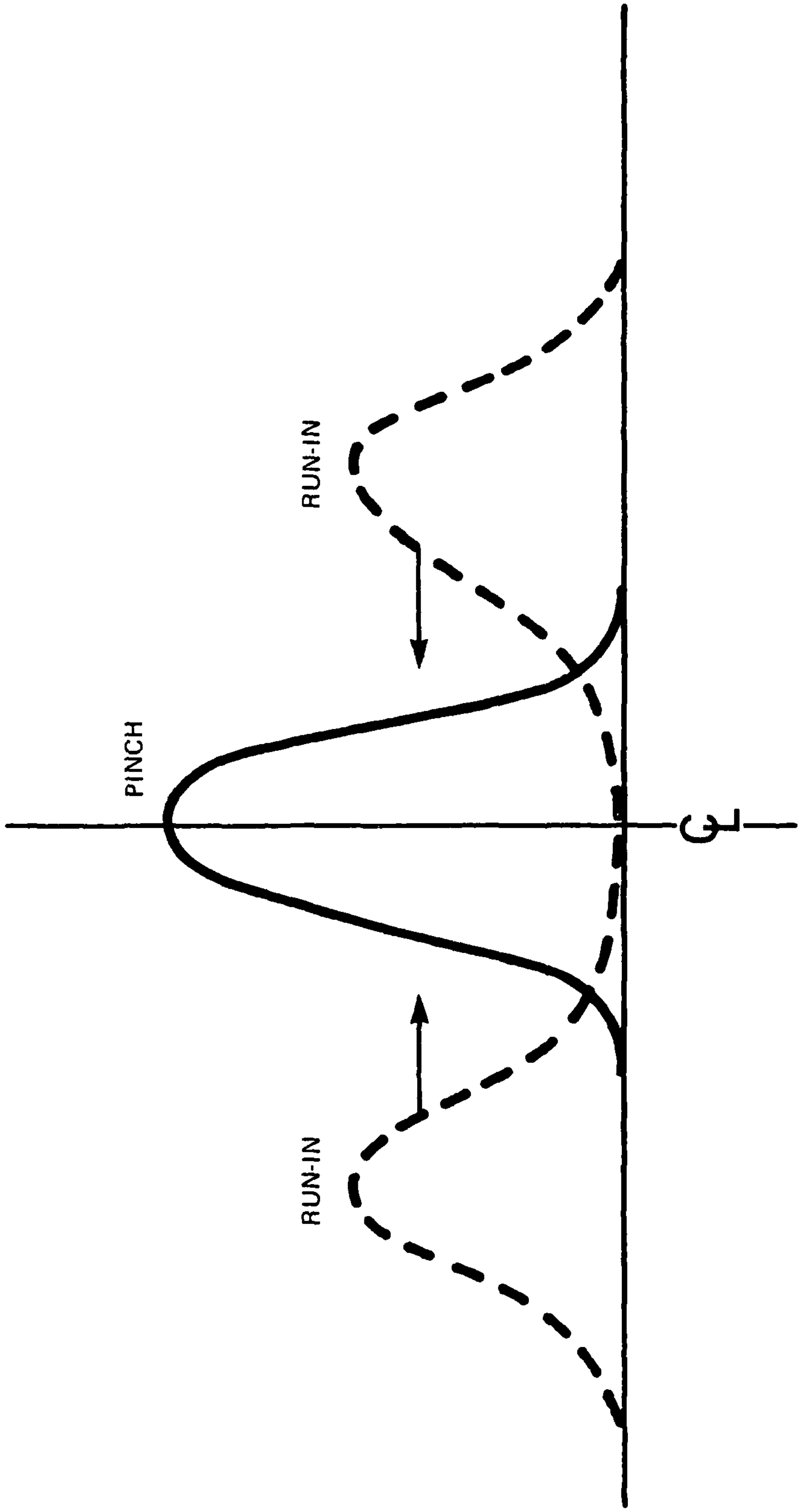


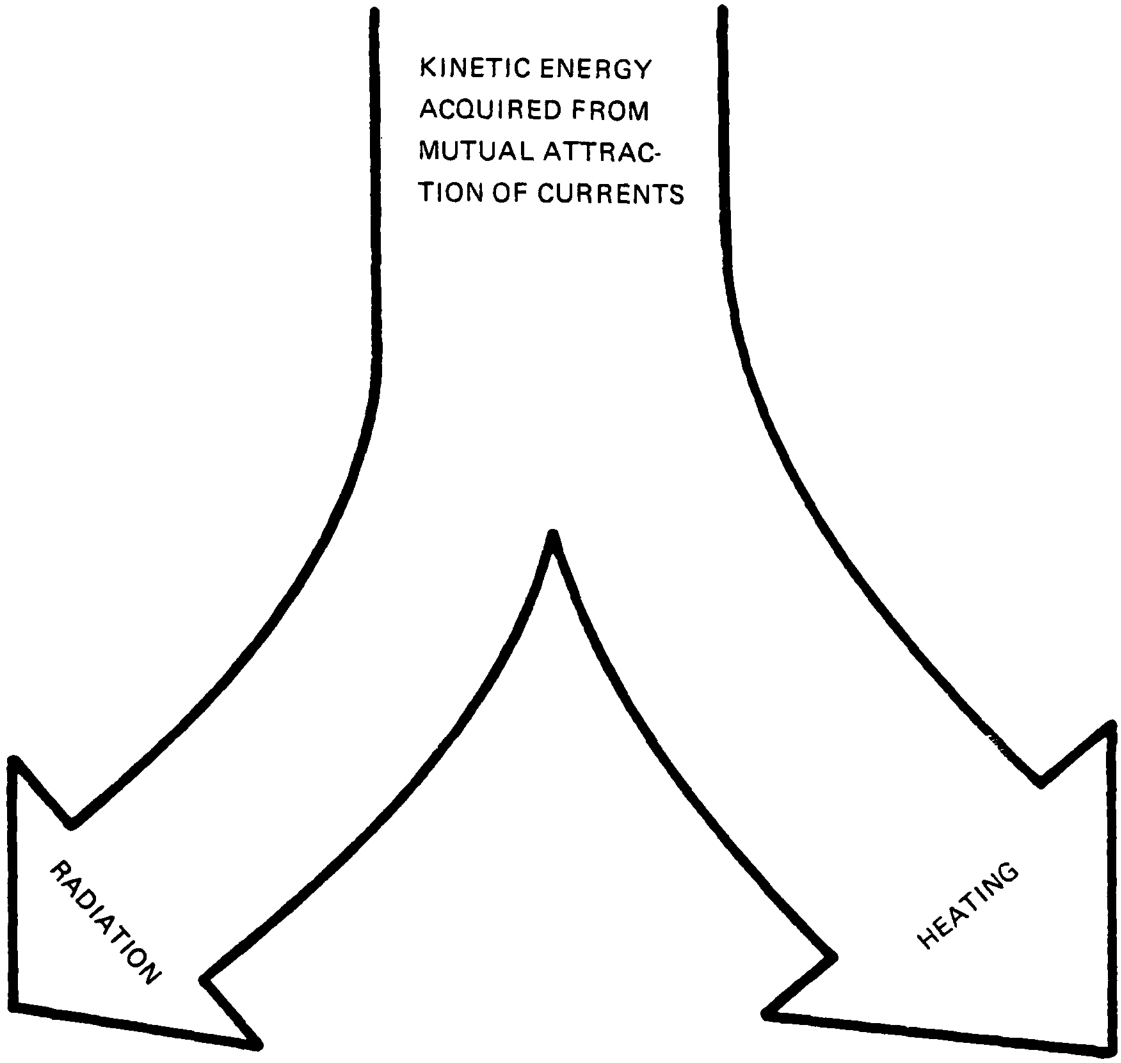
Fig. 21 — Maximum emission coefficient for a low density optically thin plasma

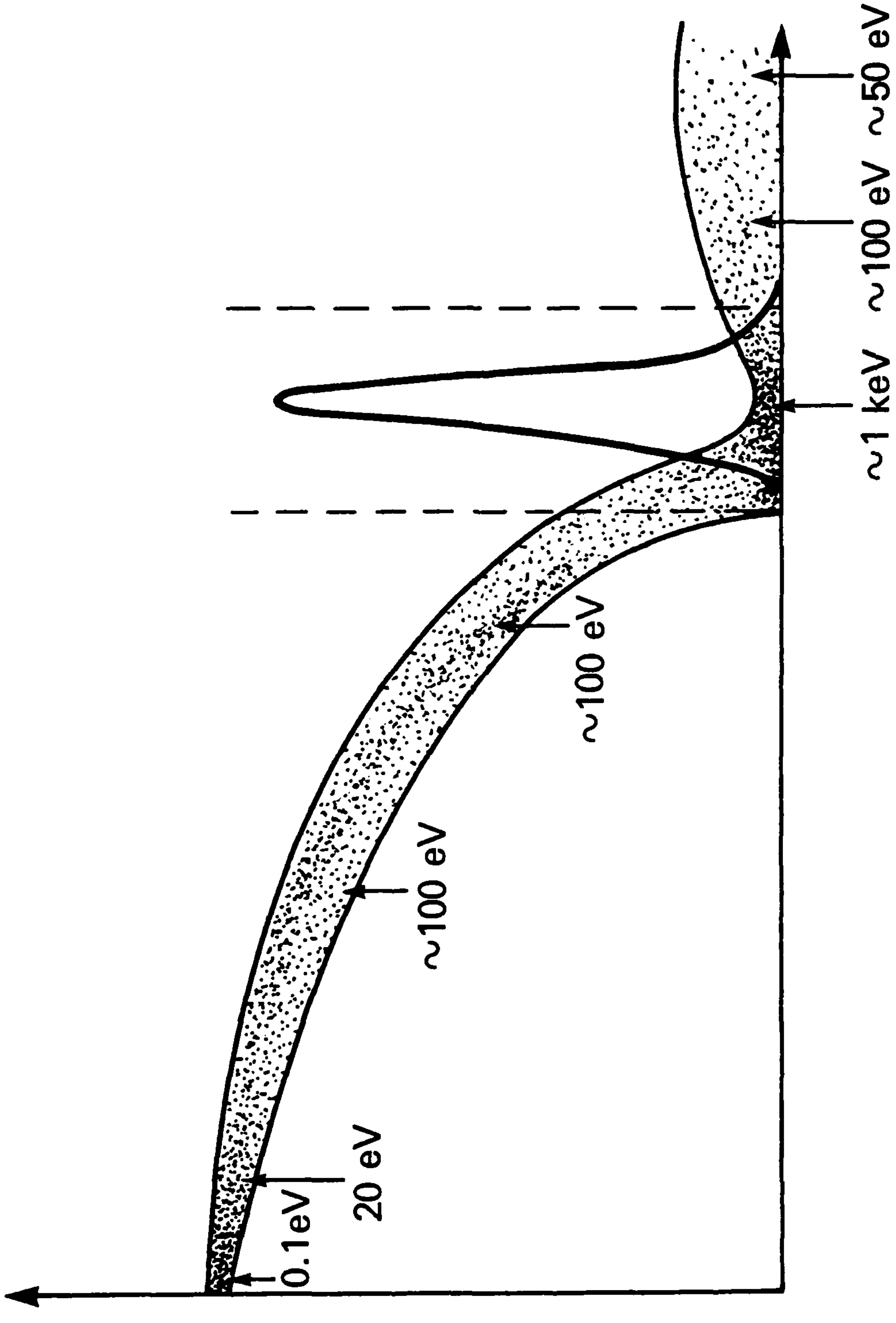

CUTAWAY VIEW
(CURRENTS FLOW
NORMAL TO PAPER)

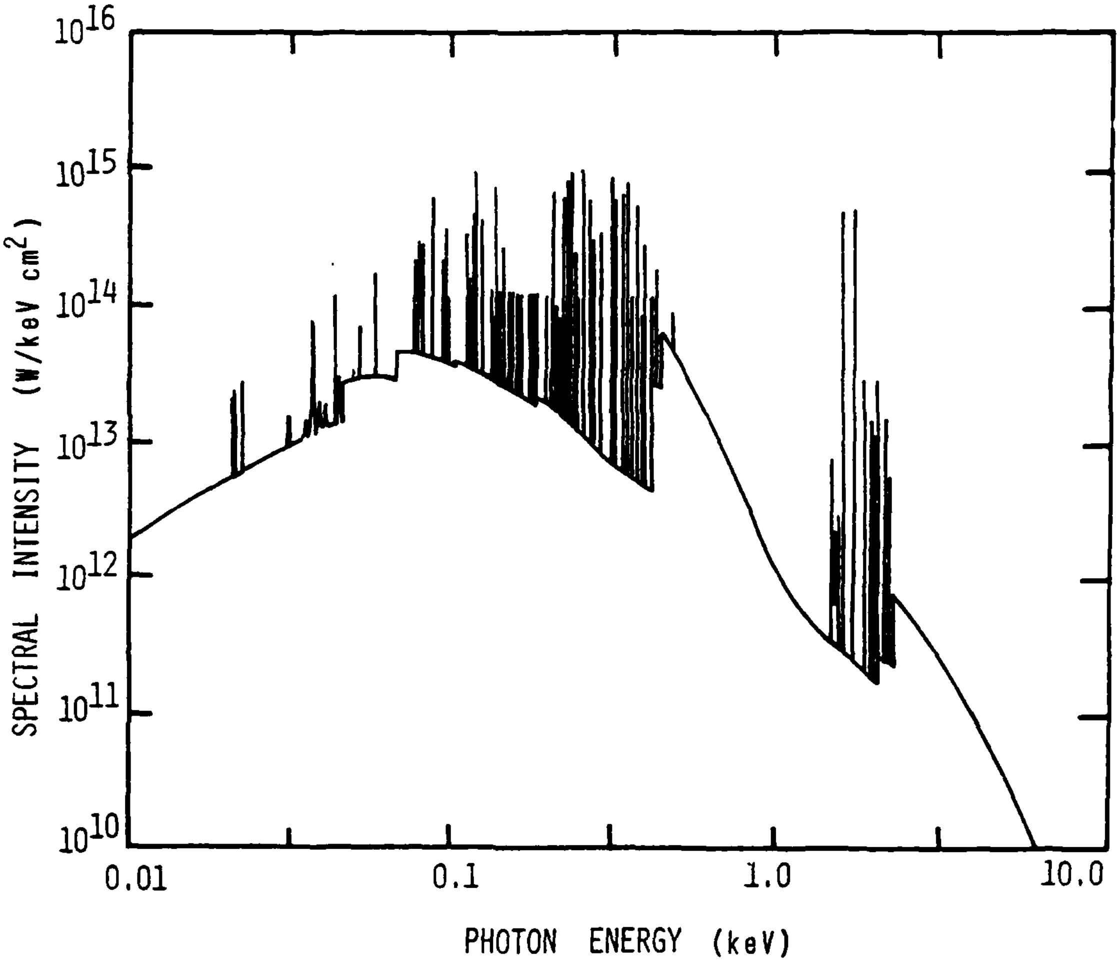

E
E
E
E
RADIAL
MASS
MOTION
CURRENT


RADIAL MASS
MOTION INDICATED
BY ARROWS

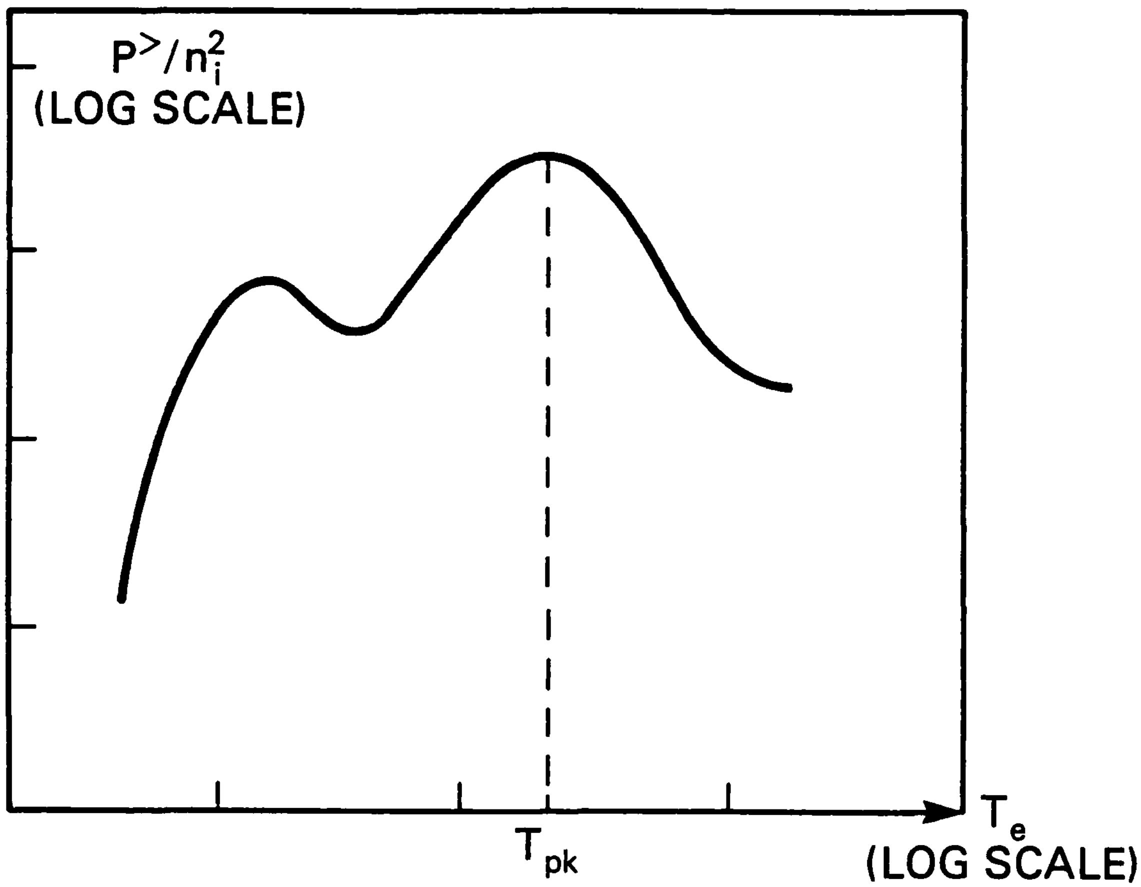

RUN-IN
PINCH
RUN-IN
ω

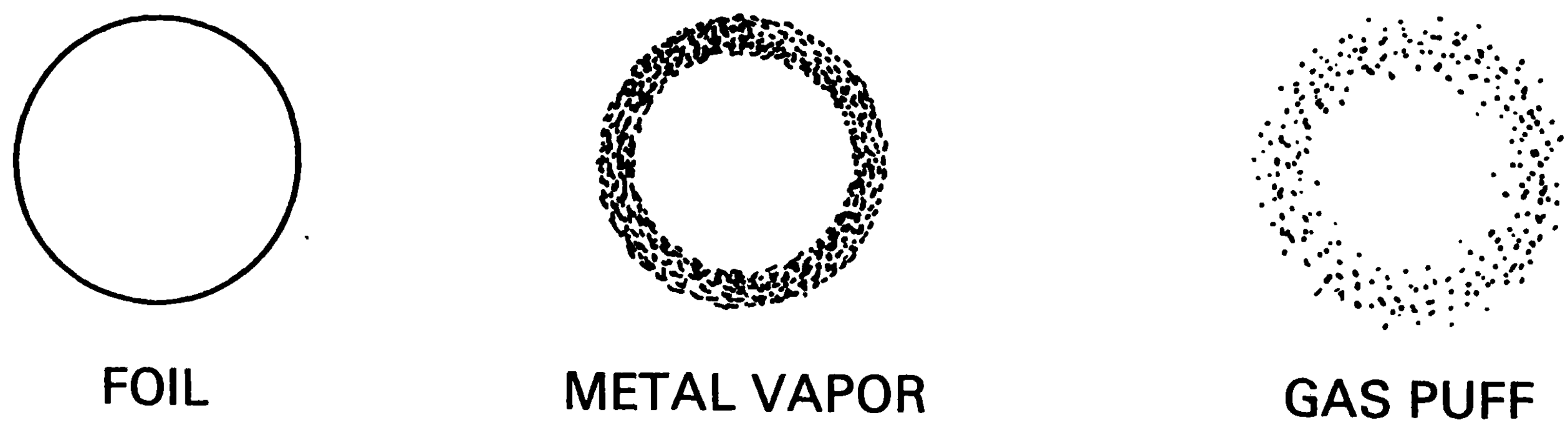

KINETIC ENERGY ACQUIRED FROM MUTUAL ATTRACTION OF CURRENTS
RADIATION
HEATING

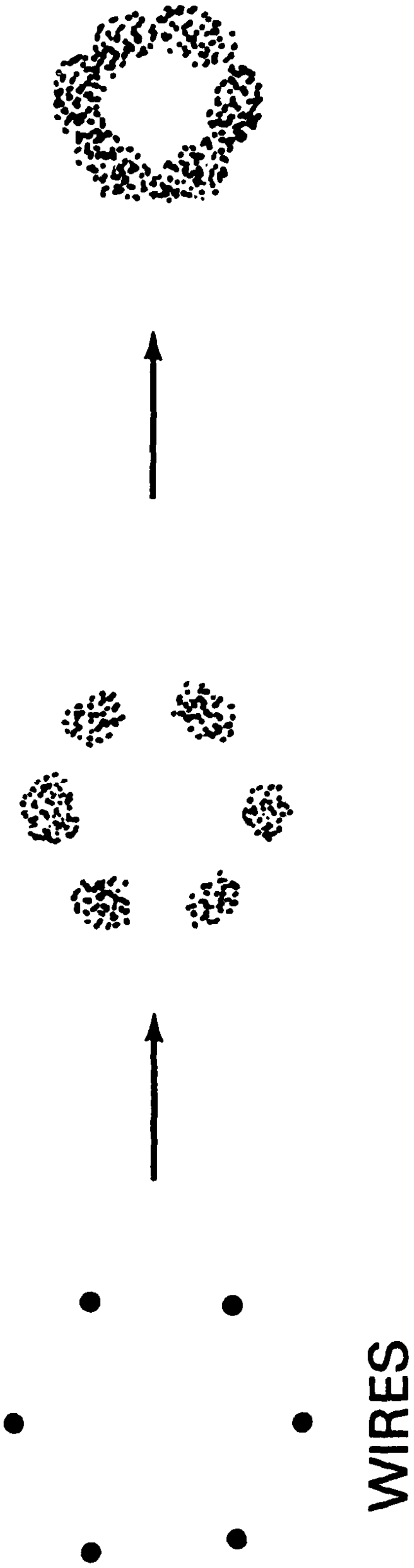

∼50 eV
∼100 eV
∼1 keV
∼100 eV
∼100 eV
20 eV
0.1eV

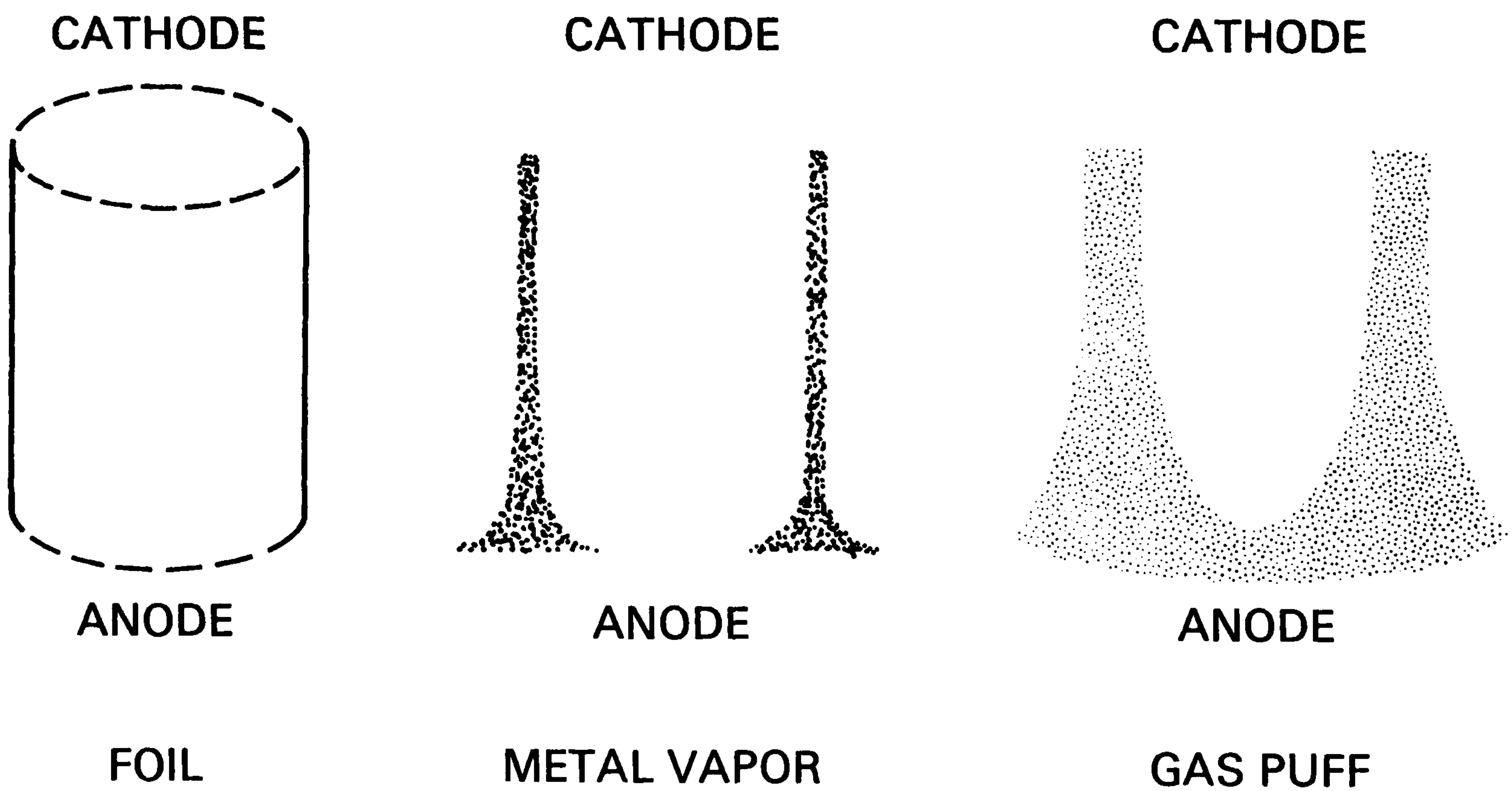


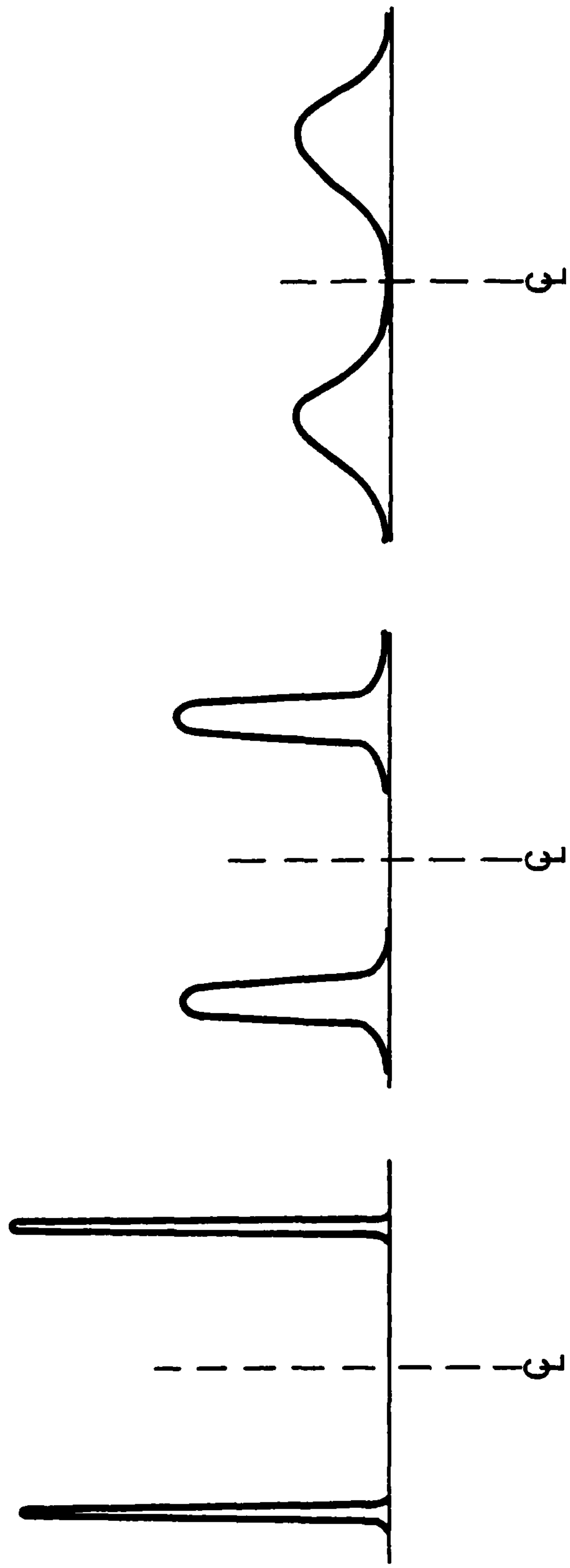
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
SPECTRAL INTENSITY (W/keV cm^2)
0.01
0.1
1.0
10.0
PHOTON ENERGY (keV)

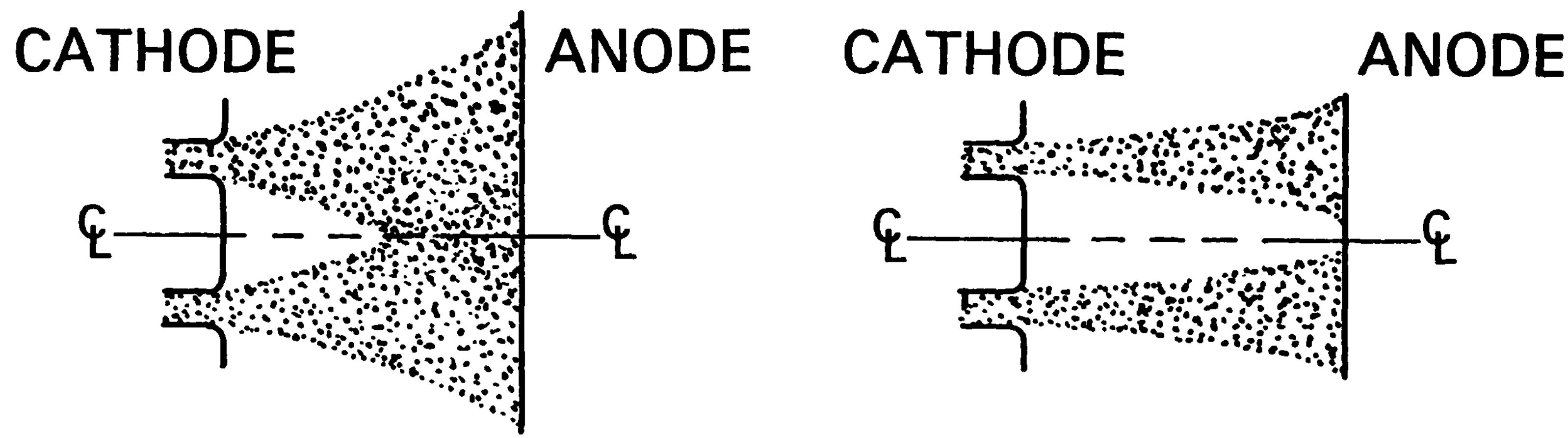

$P^{>}/n_i^2$
(LOG SCALE)
T_{pk}
T_e
(LOG SCALE)


FOIL
METAL VAPOR
GAS PUFF


WIRES

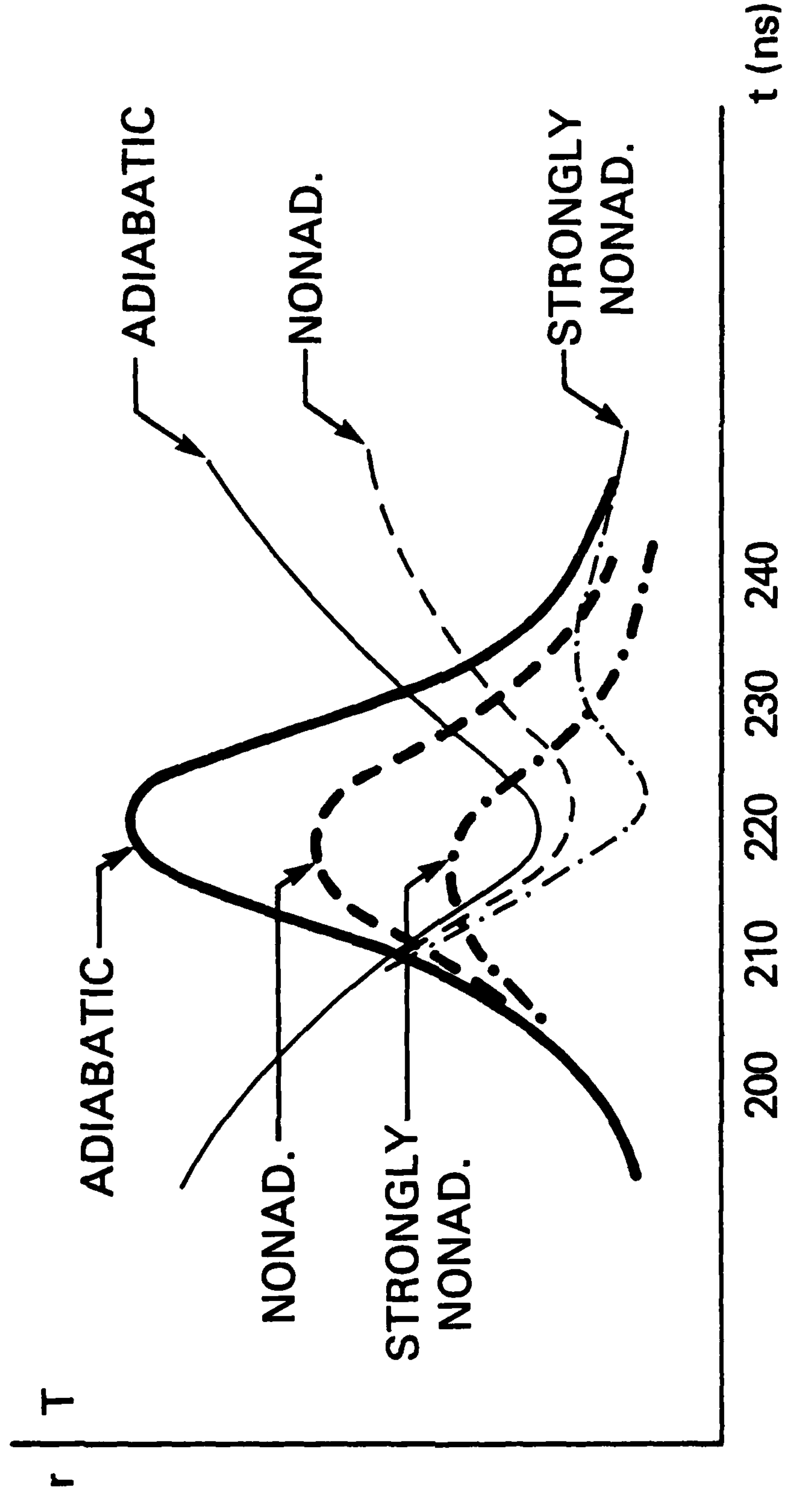

CATHODE
ANODE
FOIL
CATHODE
ANODE
METAL VAPOR
CATHODE
ANODE
GAS PUFF



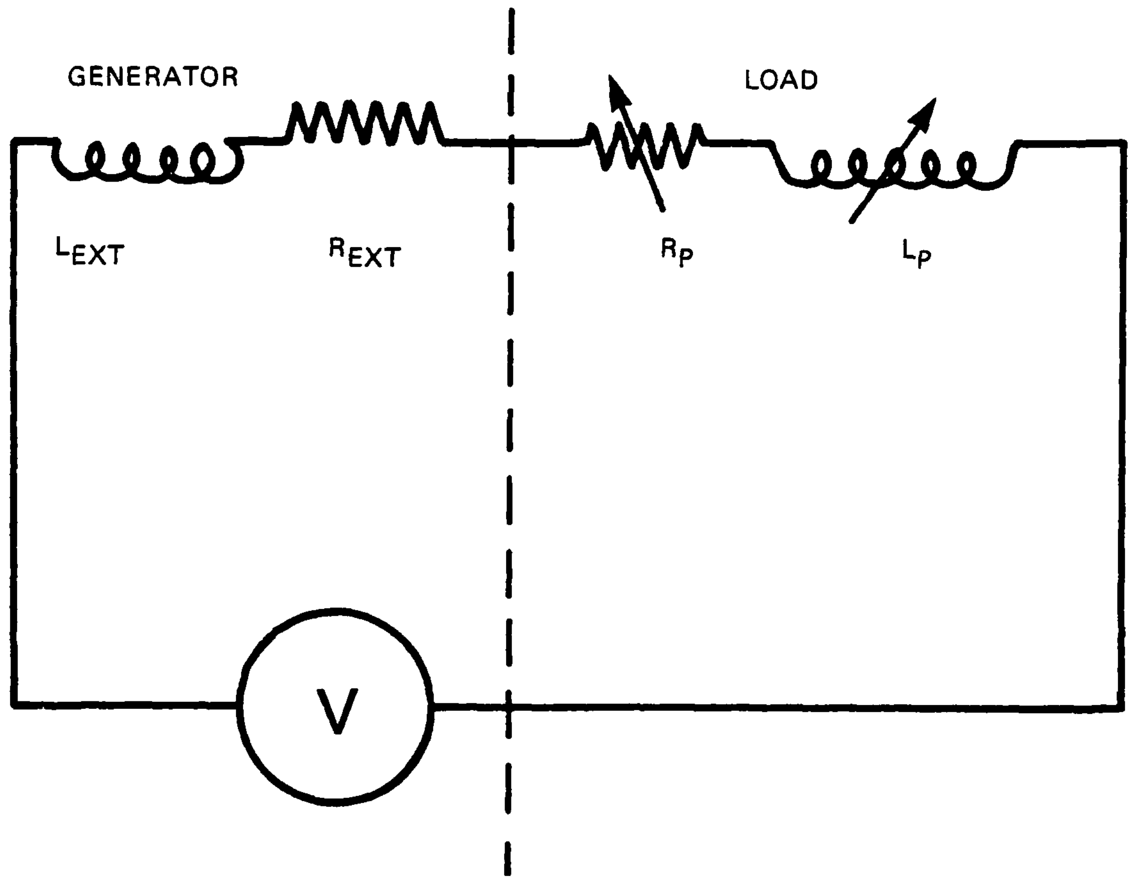


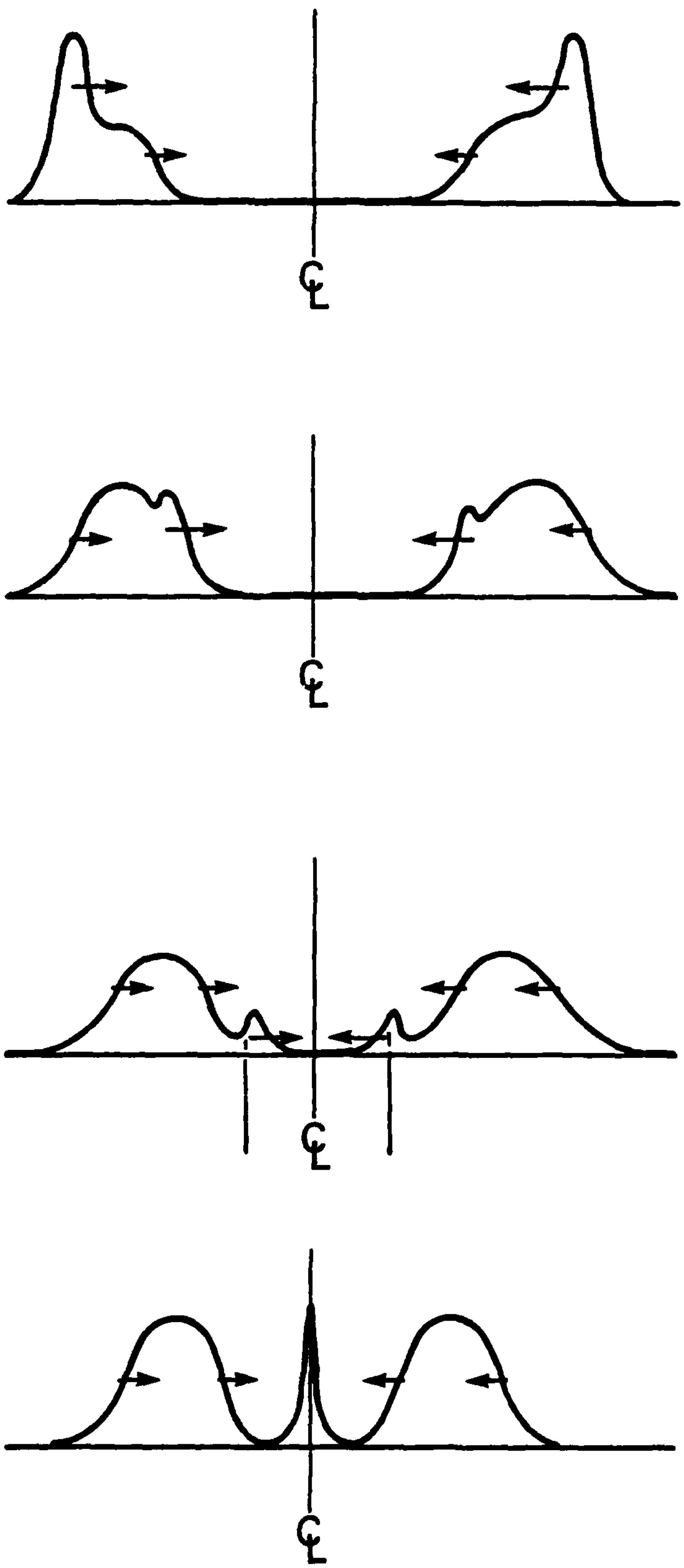
LOW MACH NUMBER

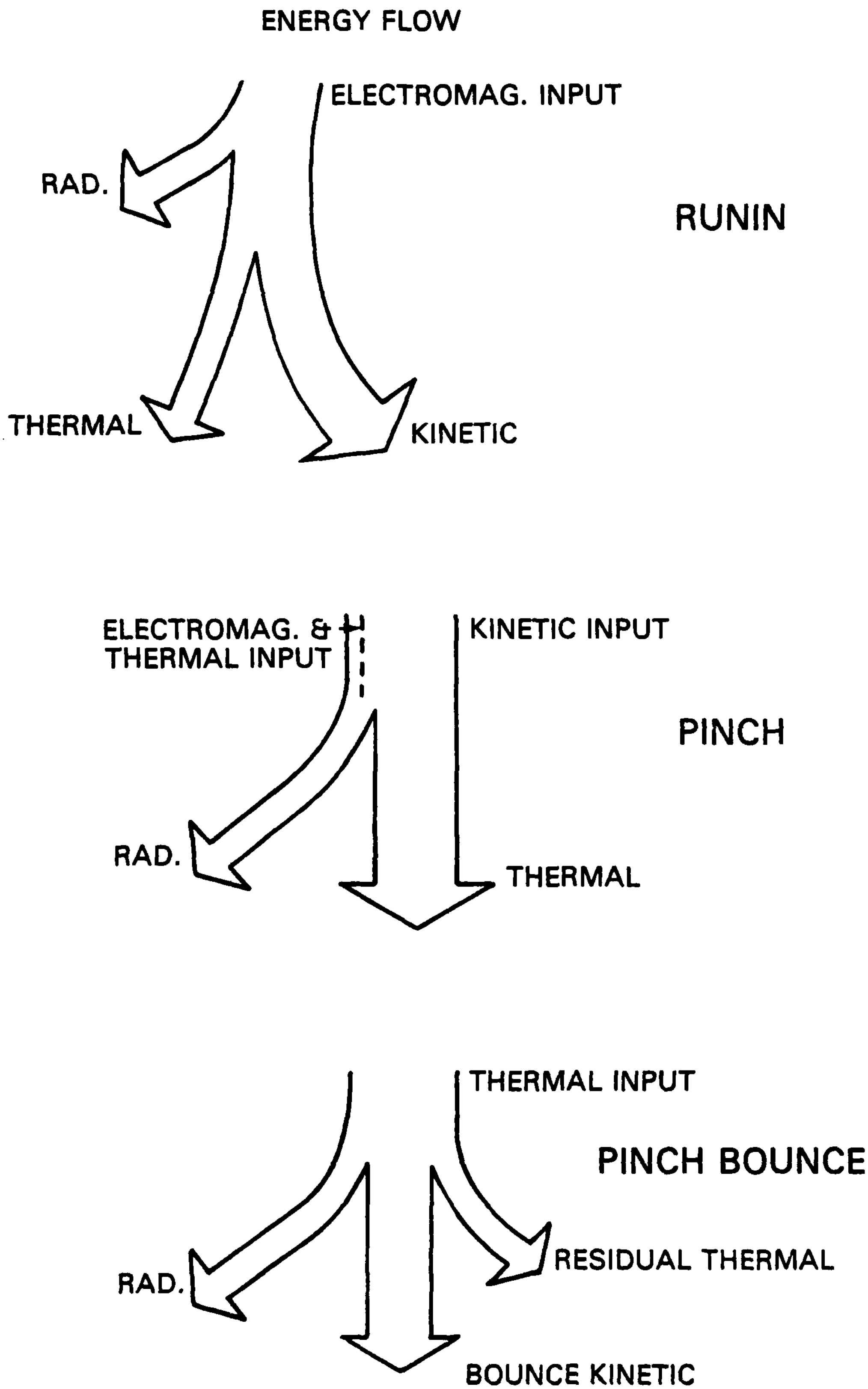
HIGH MACH NUMBER
(FASTER FLOW)

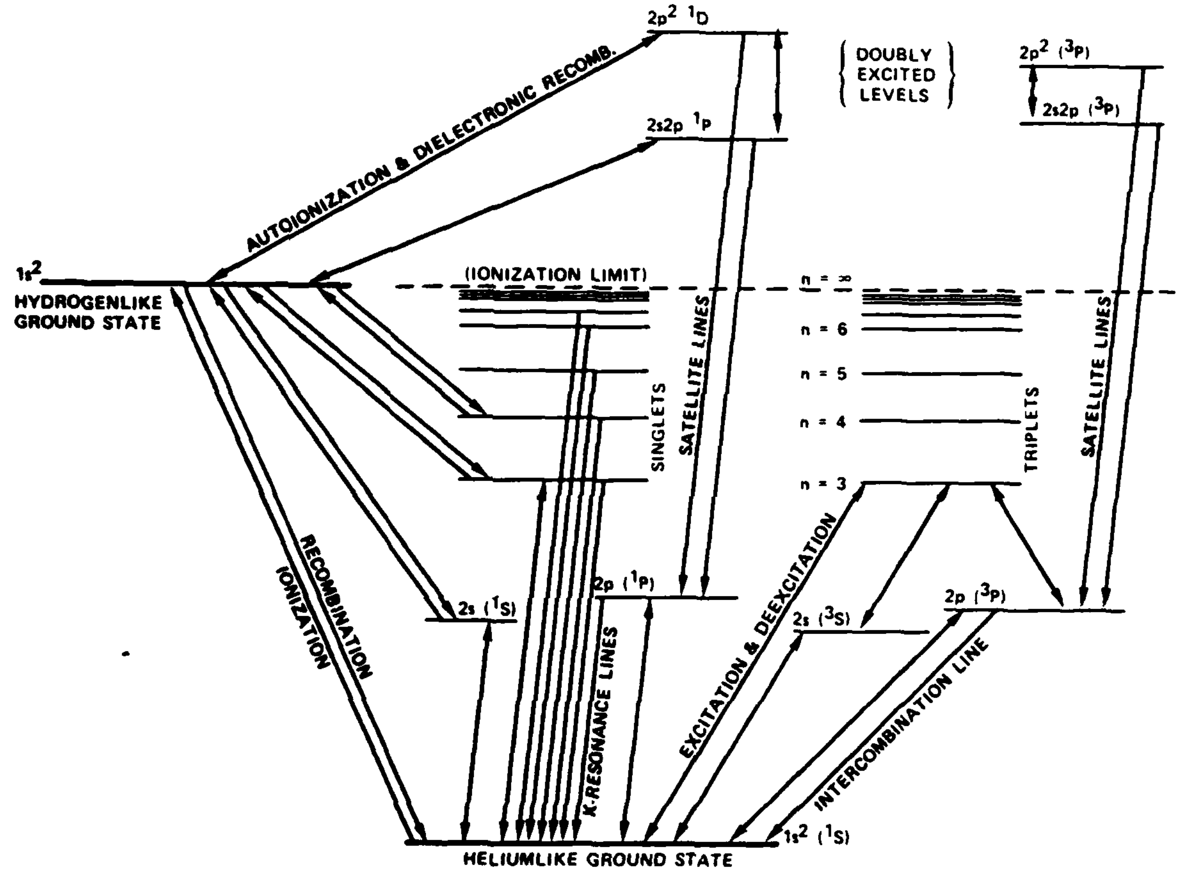


r T
ADIABATIC
NONAD.
STRONGLY NONAD.
ADIABATIC
NONAD.
STRONGLY NONAD.
200
210
220
230
240
t (ns)


GENERATOR
LOAD
L_{EXT}
R_{EXT}
R_P
L_P
V

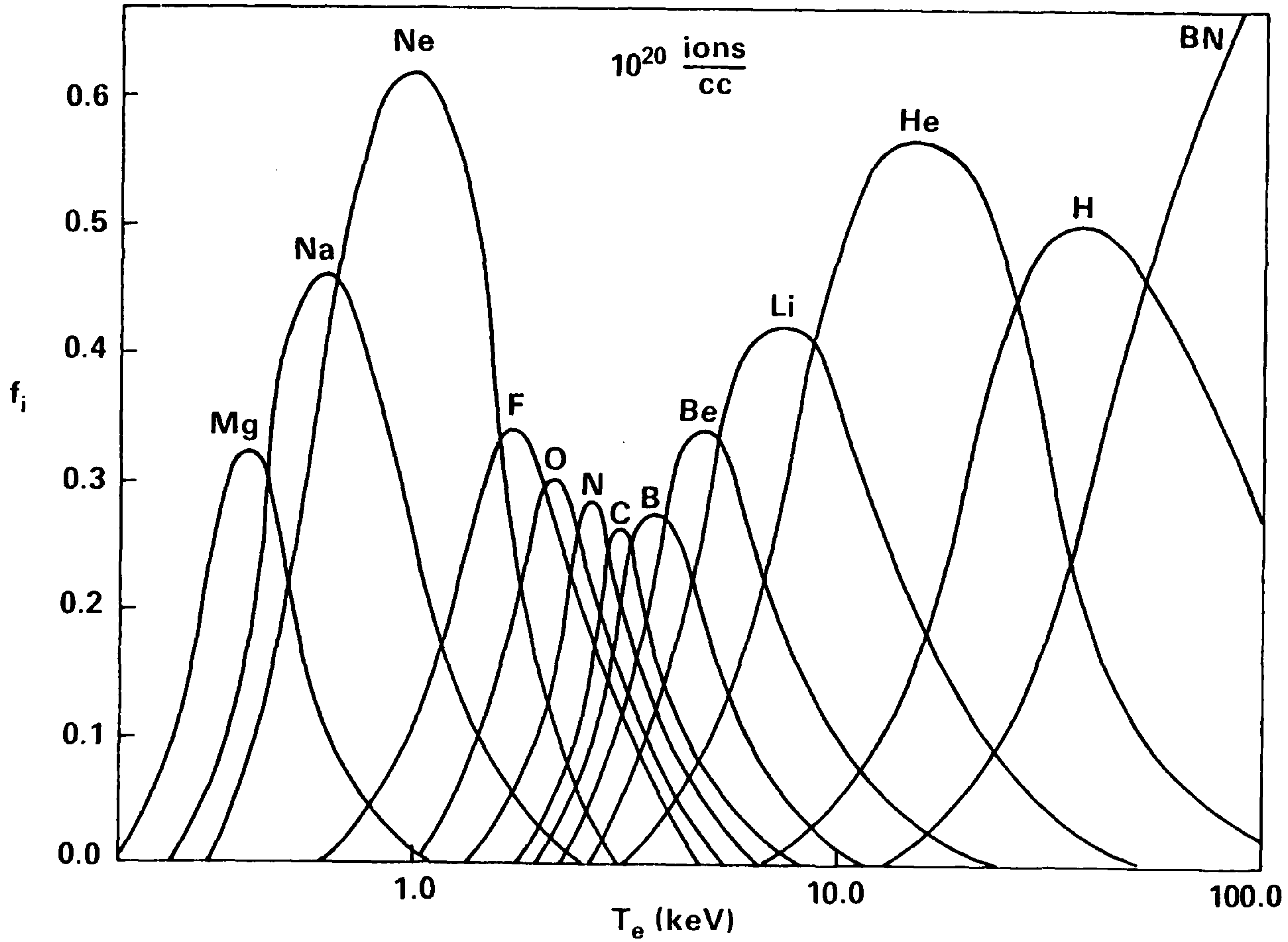


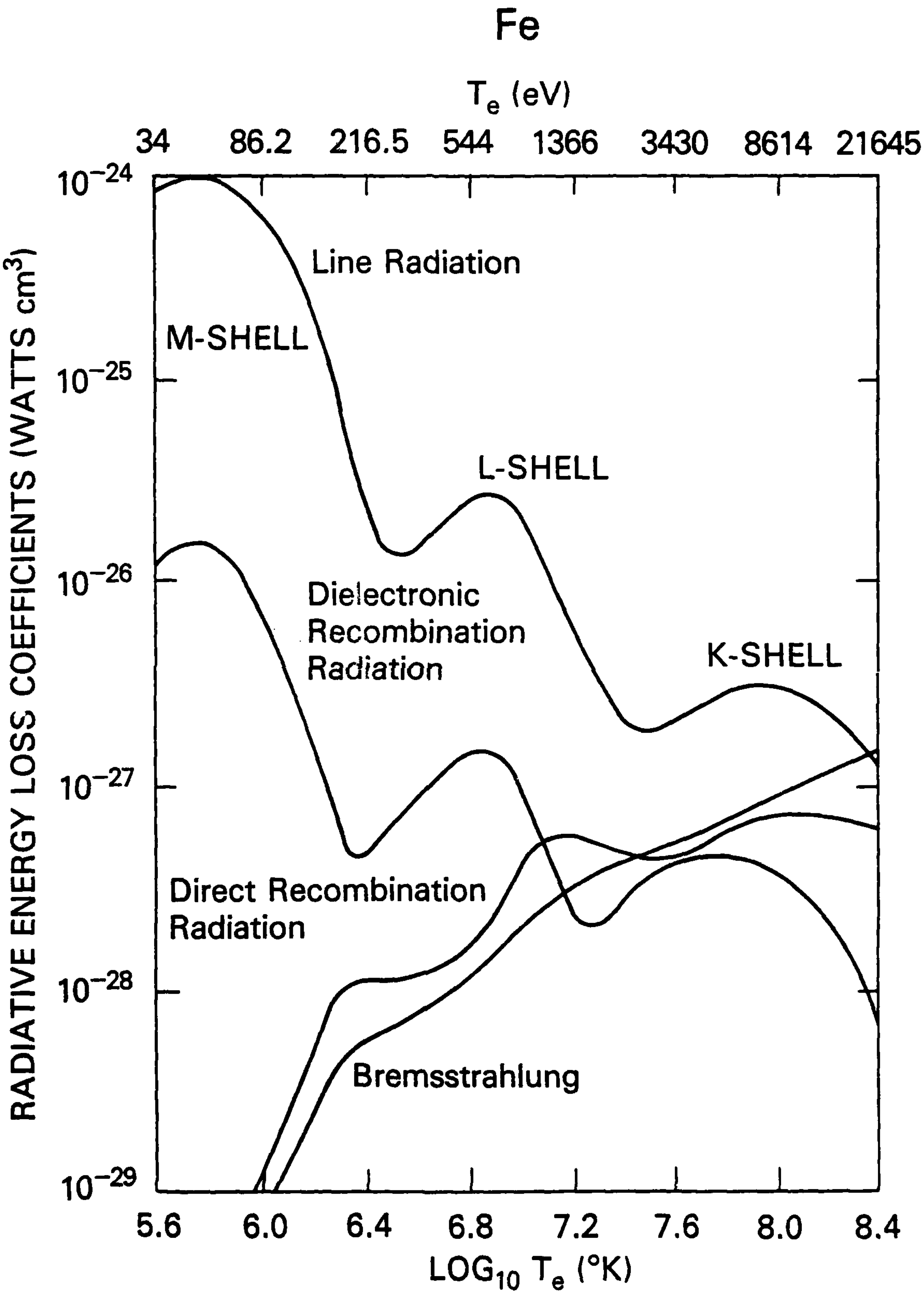

ENERGY FLOW
ELECTROMAG. INPUT
RAD.
RUNIN
THERMAL
KINETIC
ELECTROMAG. &
THERMAL INPUT
KINETIC INPUT
PINCH
RAD.
THERMAL
THERMAL INPUT
PINCH BOUNCE
RESIDUAL THERMAL
RAD.
BOUNCE KINETIC



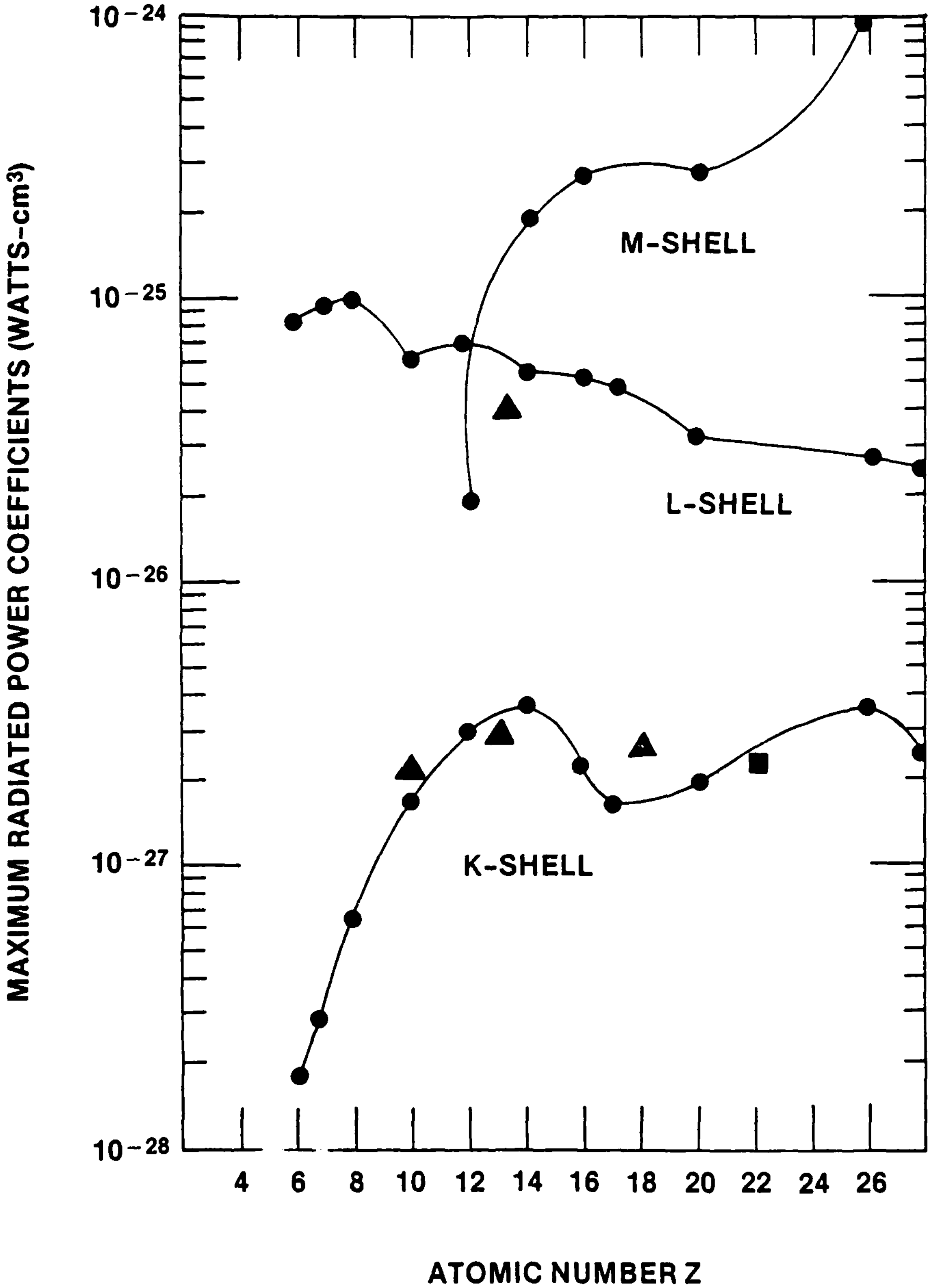
2p2 1D
2s2p 1P
DOUBLY EXCITED LEVELS
2p2 (3P)
2s2p (3P)
AUTOIONIZATION & DIELECTRONIC RECOMB.
1s2
HYDROGENLIKE GROUND STATE
(IONIZATION LIMIT)
n = ∞
n = 6
n = 5
n = 4
n = 3
SINGLETS
SATELLITE LINES
TRIPLETS
SATELLITE LINES
RECOMBINATION
IONIZATION
2s (1S)
2p (1P)
K-RESONANCE LINES
EXCITATION & DEEXCITATION
2s (3S)
2p (3P)
INTERCOMBINATION LINE
1s2 (1S)
HELIUMLIKE GROUND STATE

KRYPTON FRACTIONAL ABUNDANCES (CRE)





Fe
T_e (eV)
34
86.2
216.5
544
1366
3430
8614
21645
10^-24
10^-25
10^-26
10^-27
10^-28
10^-29
RADIATIVE ENERGY LOSS COEFFICIENTS (WATTS cm^3)
Line Radiation
M-SHELL
L-SHELL
Dielectronic
Recombination
Radiation
K-SHELL
Direct Recombination
Radiation
Bremsstrahlung
5.6
6.0
6.4
6.8
7.2
7.6
8.0
8.4
LOG10 T_e (°K)


MAXIMUM RADIATED POWER COEFFICIENTS (WATTS-cm^3)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
M-SHELL
L-SHELL
K-SHELL
4
6
8
10
12
14
16
18
20
22
24
26
ATOMIC NUMBER Z

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